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Journal
IEEE Communications Surveys and Tutorials, 20(4)

ISSN
1553-877X

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Publication Date
2018-10-01

DOI
10.1109/COMST.2018.2846284

Peer reviewed

Middleware Architectures for the Smart Grid: A Survey on the State-of-the-Art, Taxonomy and Main Open Issues

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***Abstract*—The integration of small-scale renewable energy sources in the smart grid depends on several challenges that must be overcome. One of them is the presence of devices with very different characteristics present in the grid or how they can interact among them in terms of interoperability and data sharing. While this issue is usually solved by implementing a middleware layer among the available pieces of equipment in order to hide any hardware heterogeneity and offer the application layer a collection of homogenous resources to access lower levels, the variety and differences among them make the definition of what is needed in each particular case challenging. This paper offers a description of the most prominent middleware architectures for the smart grid and assesses the functionalities they have, considering the performance and features expected from them in the context of this application domain.**

***Index Terms*—Middleware, distributed systems, software architecture, survey, state of the art.**

I. Introduction

IN ORDER to better understand the content of the paper, Table I has been included with all the acronyms that can be found in the manuscript. In this way, the definitions that are found throughout the paper can be understood right away.

Access to electricity and tools used to transform it into different kinds of energy are acknowledged as one critical aspect in sustainability and development, as energy usage is linked to every imaginable productive sector (agriculture, transport, mining, construction, industry, services, etc.) and therefore in wealth creation and transfer. However, meeting the ever-increasing demand of electricity, which usually grows in pair with the improvement of standards of living of human population and their capacity to offer goods and services, presents a collection of challenges that are difficult to solve. Commonly, the Smart Grid includes devices of very different characteristics that have to be integrated in the same system, which presents several issues in terms of their interoperability and interconnectivity at the data level. Among others, these challenges are related to the existence of different information formats used to transfer data among distributed devices, as well as providing services to the whole of the Smart Grid, and they can be accessed from higher level layers. Fortunately, there is a way to solve most of those issues by means of the implementation of *middleware*, that is to say, a distributed software layer that abstracts hardware heterogeneity and differences among devices so that it will provide the higher, more application-based levels a software architecture with a set of functionalities that will have the appearance of being homogenous and centralized for the applications that are accessing them [1], [2]. Usually, this set of functionalities will be provided as an Application Programming Interface (API) accessed by the application layer. This API can be used in an explicit way (for example, via Uniform Resource Identifiers that are invoked from Representational Transfer State-based Web services [3]), or in a more implicit manner (by using semantic queries from the applications, in order to request semantically enhanced information [4]).

A. Concept of Middleware

Middleware was first used as a concept in a North Atlantic Treaty Organization report dated back to October 1968, where it was placed between the service routines and the application programs [5]. During the 1980s it became increasingly popular due to its ability to interconnect new pieces of equipment with legacy ones within the same distributed system. As far as the Smart Grid is concerned, the services expected to be provided by the middleware are common to other software architectures used in several different systems, namely:

1. *Device registration:* This service describes how devices and the services linked to them are going to be included in the system where the middleware serving the Smart Grid is deployed. The way information is going to be transmitted from one side of the communications to the other one [6] plays a major role. Therefore, information formatting and how it is understood by every part of the system becomes a topic of major importance at this stage. If included, semantic capabilities will ensure not only that data becomes mutually intelligible among the parties involved in data exchange, but also that knowledge can be inferred from the interchanged data and aid the involved pieces of equipment to react more efficiently to unforeseen situations or data readings that involve malfunctioning.
2. *Information requests:* The Smart Grid can be used, among other things, to obtain information from the

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Digital Object Identifier 10.1109/COMST.2018.2846284

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TABLE I
ACRONYMS PRESENT IN THE MANUSCRIPT

Acronyms	Definitions
ADN	Active Distribution Networks
API	Application Programming Interface
AWS	Amazon Web Services
BaaS	Building as a Service
BIM	Building Information Models
BMS	Building Management Systems
BSD	Berkeley Software Distribution
CEMS	Customer Energy Management Systems
CNR	Cognitive Radio Network
CORBA	Common Object Request Broker Architecture
DACM	Data Acquisition and Control Management
DCPS	Data-Centric Publish/Subscribe communications
DDS	Data Distribution Service
DER	Distributed Energy Resources
DER	Distributed Energy Resource
DFN	Delayed Feedback Networks
DMS	Distributed Management System
DMS	Distributed Management Systems
DPWS	Devices Profile for Web Services
DRMS	Demand Respond Management System
DSO	Distribution System Operator
EI	Energy Internet
EMD	Embedded Metering Device
EMS	Energy Management Systems
ESB	Enterprise Service Bus
EVGI	Electric Vehicle Grid Integration
FDI	False Data Injection
FREEDM	Future Renewable Electric Energy Delivery and Management
GPRS	General Packet Radio Service
HAN	Home Area Network
IAP	Intelligent Agents Platform
ICE	Internet Communications Engine
ICT	Information and Communication Technologies
IED	Intelligent Electronic Device
INMS	Integrated Network Management
IoE	Internet of Energy
IoT	Internet of Things
LCE	Loosely Couple Event
M2M	Machine-to-Machine
MD	Mediation Devices
SCADAs	Supervisory Control And Data Acquisition systems
SCL	Service Capability Layers
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol
SSN	Secondary Substation Node
TDM	Time-Driven Middleware
TSO	Transmission System Operator
USN	Ubiquitous Sensor Network Middleware
VO	Virtual Object
VPP	Virtual Power Plants
VPP	Virtual Power Plants
WAMPAC	Wide-Area Monitoring, Protection and Control
WAMS	Wide-Area Monitoring Systems
WAN	Wide Area Network
WAP	Wide-Area Protection Systems
WiMAX	Worldwide Interoperability for Microwave Access
WSDL	Web Services Description Language
XML	eXtensible Markup Language
MDC	Meter Data Collector
MDI	Meter Data Integration
MDMS	Meter Data Management System
ME	Micro Engine
MMS	Manufacturing Message Specification
MOS	Mean Option Score
NAN	Neighborhood Area Network
NASPI	North American Synchro-Phasor Initiative
NGN	Next Generation Network
NIST	National Institute of Standards and Technology
NIST	National Institute of Standards and Technology
OMG	Object Management Group
OS4ES	Open System for Energy Services
OSGi	Open Services Gateway initiative
OSHNet	Object-Based Middleware for Smart Home Network
PAM	Power-Aware Middleware
PDC	Phasor Data Concentrator
PIM	Platform Independent Model
PLC	Power Line Communication
PLC	Power Line Communication
PMU	Phasor Measurement Units
PSM	Platform Specific Model
QoE	Quality of Experience
QoS	Quality of Service
RAM	Random Access Memory
RC	Reservoir Computing
REMS	Renewable Energy Management System
REST	REpresentational State Transfer
RPC	Remote Procedure Call
RTPS	Real Time Publish Subscriber
RTSE	Real-Time State Estimation
RTU	Remote Terminal Unit
RWO	Real World Object
SC	Service Capabilities
SCADAs	Supervisory Control And Data Acquisition systems
SCL	Service Capability Layers
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol
SSN	Secondary Substation Node
TDM	Time-Driven Middleware
TSO	Transmission System Operator
USN	Ubiquitous Sensor Network Middleware
VO	Virtual Object
VPP	Virtual Power Plants
VPP	Virtual Power Plants
WAMPAC	Wide-Area Monitoring, Protection and Control
WAMS	Wide-Area Monitoring Systems
WAN	Wide Area Network
WAP	Wide-Area Protection Systems
WiMAX	Worldwide Interoperability for Microwave Access
WSDL	Web Services Description Language
XML	eXtensible Markup Language

TABLE I
CONTINUED

devices installed and the parameters related to information harvesting, management and treatment (energy consumption, forecasting, etc.) so that they will be used by end users, staff or applications employed to monitor energy utilization among a microgrid. Middleware will handle those requests by allowing the applications

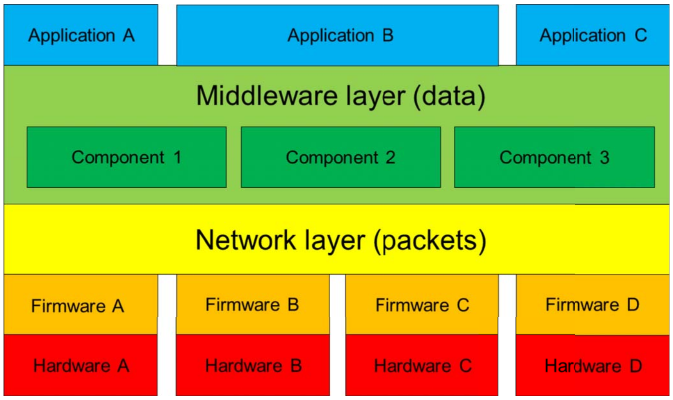

Fig. 1. Middleware location in a layered architecture.

to access the hardware devices present in lower levels, as well as by hiding the different data formats available in each of the proposals.

3. *Securitization:* By definition, a system should provide some security elements that will make it able to work in an open environment. Otherwise, any data interchange will become too risky and the usage of such a system will become jeopardized. If required to do so, middleware is capable of providing security functionalities when data transactions are made involving either its own services or the services present in the entities that it interconnects at the data level.
4. *Context awareness:* This service is strongly linked to device registration and securitization, as it will provide a framework where the actions that are being carried out can be assessed. In addition to that, it is expected from context awareness that it will be able to learn for the system what devices are available and which others are not, so the whole middleware is able to know whether there is any device that cannot be used for services or if there is another one that can cover them.

Also, it must be taken into account that middleware is usually placed between the network layer, responsible for interoperability at the packet level and network connectivity, and the application layer using data to have it represented in a comprehensible manner for human users. In that way, package information can be transferred to the application layer according to the data format used at the middleware level. Its location and surrounding elements have been placed in Figure 1.

Due to all these facts, middleware plays a major role in Smart Grid developments, as it is the cornerstone of data sharing among the distributed, Cyber-Physical System that the Smart Grid can be considered to be. Therefore, it becomes clear that how middleware is assessed and a way to evaluate how it can cover the main functionalities expected from it are topics to deal with.

B. Contributions of the Manuscript

The contributions of this manuscript can be listed as follows:

1. **Study of the most prominent middleware proposals that have been implemented for the Smart Grid.** A thorough search has been performed on the middleware architectures designed, implemented and tested for Smart Grid-related projects so as to find their most important features.
2. **Establishing of relevant criteria on how to characterize middleware proposals for the Smart Grid.** The number of services that are used, the computational capabilities required for them to be operational, how messages are coupled when they are sent from one device to another one.
3. **Identifying the main open issues and challenges inferred from the study done in the State of the Art.** After all the proposals have been reviewed, it can be inferred how the currently available middleware proposals deal with the functionalities obtained from middleware (hardware abstraction, service availability, etc.).
4. **Putting forward procedures to solve those issues and standardize the development of middleware according to what is needed from it.** Considering the present issues, it can be known how to tackle them to an extent so that the next proposals that are conceived improve the existing State of the Art in middleware for the Smart Grid.

C. Organization of the Article

This manuscript is organized as follows: Section II contains the four main features and criteria that have been used to assess each of the middleware architectures, along with a description of how they can vary from one stage to another. Section III contains the taxonomy that has been created for middleware study, as well as how it can be used to both evaluate the existing middleware solutions and design a middleware proposal for a specific environment. The study itself of all the proposals is contained in Section IV. Each of them has been described and evaluated considering the criteria of Sections II and III. Open issues have been considered in Section V. Finally, conclusions and future works are put forward in the last section.

II. Classification and Background of Middleware for the Smart Grid

The existing plethora of middleware proposals for the Smart Grid is challenging to evaluate, due to the fact that proposals widely argue about what middleware is and what can be regarded as such. Sometimes middleware is mentioned as a concept that is not fully implemented, whereas in other cases middleware includes facilities that belong to immediately higher and lower layers, such as networking and application ones. The benefits that having a middleware layer involve how it is able to provide solutions to challenges present in distributed systems that are related to interoperability and data transmission. Table II reflects those issues and how they are solved. Additionally, it also shows the features related to middleware that have to be considered in order to make possible to find a solution.

TABLE II
SMART GRID CHALLENGES AND HOW THEY ARE SOLVED BY MIDDLEWARE

Challenge	How middleware solves it	Related feature
Hardware interoperability	Hardware abstraction of the deployed hardware components	Service availability
System services (context awareness, semantics, device registration)	Services deployed in the middleware architecture	Service availability
Service performance	Middleware services running on the hardware	Computational capabilities
Interconnectivity data level	Information parsing so it can be understood in the whole deployment	Message coupling
Information availability	Information transfer among involved entities	Message coupling
Data collection	Data queries among deployed devices	Middleware distribution
Data centralization	Distribution of middleware among deployed devices	Middleware distribution

As it can be seen, there are four different features that, according to the authors of this paper, must be taken into account when describing a middleware proposal because of their importance in the conception of a middleware solution. Those features can be regarded as of major importance to understand the classification and the study that has been carried out for middleware solutions in this manuscript. They are as follows:

1. *Service availability:* The number of services that are offered by a middleware architecture can differ depending on the purpose that it has been conceived for. Typically, the more services available for a solution, the more useful and flexible it will be. This feature is of major importance due to the fact that it will be describing the amount of facilities that can be provided by middleware, should the other components deployed in the Smart Grid be incapable of handling those software services. Service availability is cited as one feature of major importance in systems related to telecommunications (having Highly available systems has been cited as the cornerstone of telecommunications industry [7]) and storage (middleware is advisable to be used for High-Availability Storage Services, [8]).
2. *Computational capabilities:* A problem with the former feature is that services might be not available for certain scenarios, due to the capabilities of the hardware that is expected to have them installed, thus making necessary to take it into account. This characteristic is important because if there are not powerful enough hardware resources to run the system, the middleware services and facilities will not be able to be executed. The importance of computational capabilities when still having functional middleware has been described in [9] (where it is claimed that middleware for the Internet of Things "*should offer, among other things, functional components necessary for service discovery, service composition, data management, event management and code management*") or [10] (where it is claimed that "*We believe that middleware solutions designed specifically for low powered resource constrained computation devices are critical in order realise the vision on IoT*"), where middleware is specified for the constrained resources environments of the Internet of Things and mobile devices, respectively.
3. *Message coupling:* There are several ways to transmit messages among the entities interconnected by middleware. Depending on the time constrains in the interchange of information, it can be argued that coupling of sending and receiving data will be a matter that will play a major role in the services available in the middleware proposal. The importance of message coupling lies in the fact that, depending on the specific needs of the system, middleware might have to be used when either real-time information delivery is needed or a subscriber retrieves the information previously published to transfer it to the application layer [11]. Many other authors also recognize the need to introduce message coupling in middleware architectures depending on the conceived architecture ("*It is well accepted that different types of distributed architectures require different degrees of coupling*", [12]).
4. *Middleware distribution:* While it is expected that middleware will be distributed to an extent, there are several degrees of distribution depending on the needs of each of the proposals and the functionalities that they have been designed to fulfill. Although it is usually considered that middleware should be as distributed as possible, there might be specific cases where full distribution may not be possible or could be counterproductive. For instance, middleware can be included as part of a distributed

mobile cache platform [13]. Another example is [14], where a system is shown with Quality of Service specifically related to the degree of middleware distribution in a deployment.

If these four main features are to be displayed in a more specific way, each of them can be regarded as an axis where there will be a range of values going from a minimum (for example, minimum distribution) to a maximum one (for instance, maximum message coupling), along with several intermediate levels used for more accurate characterization of the features previously described. Each of the features, the reasoning behind choosing them as a way to assess a middleware proposal, and their minimum, maximum and intermediate levels, have been included in the next subsections of this manuscript.

A. Service Availability

This feature deals with the quantity of services offered by the middleware proposals evaluated. It is not uncommon for a system related to the Smart Grid having services located in the middleware rather than in hardware devices or applications: hardware available could have too little capabilities, or applications required to work with such a little computation footprint that they cannot encase some functionalities that would be offered by their own proprietary software otherwise (security, semantic capabilities, registration, context awareness, etc.). Therefore, the assessment of these features is of major importance so as to understand the capabilities of a middleware solution in this application domain. In addition to that, it is also considered whether these services are offered to entities outside the middleware proposal (and therefore are providing a functionality to the hardware and software components located above or below middleware) or are used just to provide some support or expected internal functionality of the middleware. Four different levels have been defined for this feature:

1. Abstraction middleware: the sole objective of this kind of middleware is isolating all the hardware differences and heterogeneity to the upper levels of a layered system. It is the original functionality that middleware was conceived to accomplish [15].
2. Intermediation middleware: in addition to the previous functionality, middleware solutions based on this approach offer one more sublayer used to provide access points for the application layer located right above it, as a way to externalize functionalities that cannot be offered by the applications themselves [16].
3. Message-Oriented Middleware: in this case, the middleware proposal offers a set of messages as a way to format the data transferred through the system. Messages will usually contain several fields where information is encased according to a set of rules (content, length, etc.). They will be shared among participants of the system regardless of their location [6].
4. Middleware architecture: at this level, the services that are offered go beyond what is usually expected from middleware. Services provided for a middleware architecture will range from access securitization to context awareness. It can be deemed as the most complex possible way to provide services by middleware. One case of this kind of development is Enterprise Service Bus architectures [17], which have been designed to interconnect at the data level different applications in a bus that will transfer information from one side of the communication to the other, regardless of how the applications are programmed or other implementation details (programming languages, etc.).

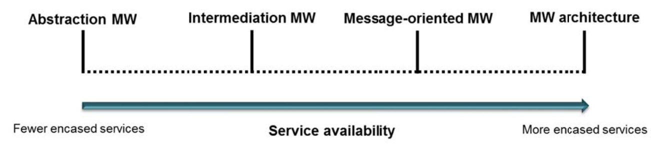

Fig. 2. Rank levels of service availability.

In a more graphical way, the assessment of this feature can be done with an axis as the one presented in Figure 2. The subjacent characteristic that guides the established levels is service availability in the middleware solution.

B. Computational Capabilities

This feature has been conceived to take into account the necessary hardware that has to be used in order to run the proposal in the devices that have been included as part of the Smart Grid-like deployment. If the middleware proposal demands too many hardware resources there will be certain devices related to this application domain, especially at the end user location (Advanced Metering Infrastructure, sensors) that will not be able to have the middleware installed in them, which will have consequences in the level of decentralization that can be offered. Some of the proposals that have been reviewed are somewhat related to other developments linked to the Internet of Things and Cyber-Physical Systems that resemble them, so those proposals can be ported to those application domains to an extent. There are four different levels that have been defined for computation capabilities:

1. End user domain devices: these are the pieces of equipment present in the end users' dwell or facility. If the Smart Grid is fully implemented, they will be the ones present as part of the prosumer facilities. Typically, the devices that will be present in this domain will be based on Advanced Metering Infrastructure, which it is close to other application domains resembling the Smart Grid, such as the Internet of Things [18]. Home batteries or other forms of energy storage can also be regarded as end user domain devices, as they can be used for energy storage and trading by a home dweller if they are willing to do so [19].
2. Aggregator domain devices: the devices that would be included here are used by the aggregator (or the retailer that sells the electricity to the end users, depending on the particularities of the power grid) to perform its functionalities, which may involve either transferring electricity among a cluster of users (if the aggregator is fully enabled) or only selling it to the end

users. Databases utilized as a way to store information or energy scheduling algorithms will also share the hardware expected to be used [20].

3. TSO/DSO domain devices: the devices present in this domain are usually accessed via engineers, researchers and technicians installing, designing or troubleshooting the equipment used for the transmission and distribution of electricity. Examples of these kinds of equipment are phasor measurement Units (PMUs) used to synchronize measurements on an electric grid for control and monitoring functionalities [21], and Remote Terminal Units (RTUs) for demand response execution between the DSO and end users present in a system [22].
4. Power plant domain: this has been regarded as the place where power is produced as a result of the transformation of an energy resource, regardless the one that is used in this procedure (non-renewable or renewable). It is likely that the facilities present in this part of the application domain require large computational resources, as they imply management of large quantities of information from the grid (big data applied to the Smart Grid [23]) or the execution of demanding algorithm implementations for knowledge inference (machine learning in this application domain [24]).

The appearance of all the levels that have been established to assess this characteristic have been depicted in Figure 3.

C. Message Coupling

This feature is used to evaluate the speed at which messages that are generated by one entity are consumed by the one that is expected to receive them. Depending on the specific case, there will be different needs for the messages that are being transferred; as some of them must be sent as soon as possible whereas other might be stored until they are requested by an interested party. In this way, message coupling is closely associated to the need of delivering the information that is required. The four different paradigms that have been used to assess message coupling capabilities are the following ones:

1. Publish/Subscribe paradigm: under this kind of paradigm, the entities interested in a subject of the transmitted information are subscribed to another one involved in the system that is capable of publishing information of their interest. Subscribers will manifest their interest in some kind of information before receiving any, so that when publishers make it available, it will be redirected to the subscribers. Proposals making use of topics usually favor this approach, as they have been built with the idea of separating the content depending on the topic that is used to characterize it [25], [26].
2. Polling paradigm: in this case, data are stored in a specific location until reclaimed by a client to consume it [27]. Rather than having the information as soon as possible, the main stress in this paradigm is information availability.
3. Client/Server paradigm: this paradigm is used in a way that the data present in one side of the communication (the server) will be requested to be offered by another entity that will perform a query to obtain it (the client), as it is done in many distributed systems [28]. This is a communication model usually found in Internet-related applications and is utilized by middleware proposals mimicking it.
4. Real-time paradigm: unlike previous cases, the main priority for this paradigm is the fast delivery of information. While the requirements of a communication to be considered as real-time can vary depending on the parameters used in each of the cases, they will imply the delivery of the information in a period of time short enough to be regarded as negligible by the application where it is utilized [29].

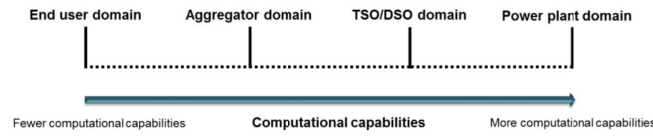

Fig. 3. Rank levels of computational capabilities.

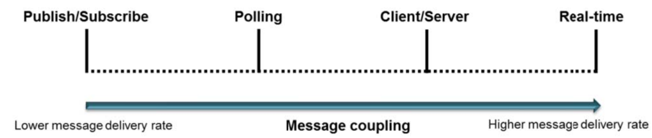

Fig. 4. Rank levels of message coupling.

The axis that has been defined for this feature can be seen in Figure 4. As it happened in other cases, it has to be noted that the presence of one level or another does not make it a better or a worse middleware proposal, but one that has been conceived for certain objectives that may or may not be matching what should be offered by middleware for the Smart Grid, depending on the criteria of the authors of this paper.

D. Middleware Distribution

This feature measures how many devices in a deployment have any partial implementation of middleware installed in them. It is usually considered that middleware should have a significant degree of distribution, so that it can be accessed by all the hardware devices and network infrastructure that it is trying to withhold in terms of heterogeneity and complexity. Taking this aspect into account, four different levels of middleware distribution have been defined:

1. Fully centralized middleware: middleware is located in one single device used to perform all the functionalities conceived for it. While this might not be an optimal solution to accomplish those functionalities, there could be other features of the system (hardware limitations, resource unavailability) that prevent having the middleware proposal distributed in any other way [30].
2. Mostly centralized middleware: it is basically installed in one specific device (or in several of them that are effectively behaving as a single one), but some of the

TABLE III
JUSTIFICATION OF THE STUDIED FEATURES AND REFERENCES SUPPORTING SUCH JUSTIFICATION

Feature	Justification	References to support justification
Service availability	Required for hardware abstraction and service availability for the upper and lower layers	[6], [7], [8], [15], [16], [17]
Computational capabilities	Required to know what hardware devices can run middleware	[9], [10], [18], [19], [20], [21], [22], [23], [24]
Message coupling	Required to know how information is parsed and transfer times and capabilities	[11], [12], [25], [26], [27], [28], [29]
Middleware distribution	Required to know the amount of devices can run the middleware in a deployment	[30], [31], [32], [33]

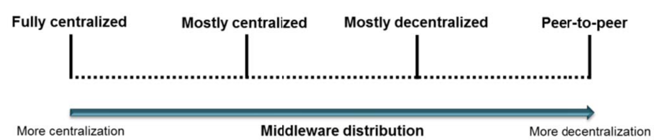

Fig. 5. Rank levels of middleware distribution.

components that are part of it have been located in other pieces of hardware [31].

3. Mostly decentralized middleware: the different software components that make possible the middleware solution have been deployed in several hardware devices in this case. However, there is an underlying hierarchy that is keeping the most prominent ones in a piece of equipment or in a reduced number of them to an extent [32].
4. Peer-to-peer middleware: in this case, there are no central elements that have been given more ruling functionalities than others. This paradigm is used in some applications that favor the interchange of files or information where no centralized entity is providing any management or command, such as in file sharing systems [33].

The axis that has cbution of the studied proposals has been included in Figure 5.

As it was previously said, the existence of such a classification with different features does not imply that a solution is inferior to others that solve their challenges in a different way, but that it does not match the criteria that has been used by the authors of the proposal to assess what a middleware architecture for the Smart Grid should consist of.

III. Taxonomy for Middleware in the Smart Grid

If the previous sections are taken into account, it can be understood that there are strong reasons to use service availability, computational capabilities, message coupling and middleware distribution as the main characteristics of a classification of middleware for the Smart Grid: they are needed to know how hardware is abstracted, the power of the devices running the middleware, how information is transferred, or the amount of devices that have middleware deployed. In addition to that, literature supports these claims judging from a significant amount of works that have reached comparable conclusions. Table III summarizes these aspects in this manuscript.

Considering all the already explained features and their different degrees, a taxonomy has been created in order to classify all the different solutions that have been studied. The taxonomy takes into account the different levels that the previously described four features can have, so when a system has to be described according to its characteristics, it will be done so according to the different levels that have been described for service availability, computational capabilities, message coupling and middleware distribution. The appearance of this taxonomy can be seen in Figure 6.

As depicted, each of the features that have been chosen to evaluate the different proposals for middleware is one major category of the taxonomy, whereas each of the subcategories included in the larger categories is used as a way to obtain further information about how the feature was implemented in each of the proposals. An interesting aspect of this taxonomy is that it can also be modified in a way that will make possible to evaluate each of the proposals as features in a matrix that characterizes middleware solutions for the Smart Grid. In this way, the rows in the matrix would be used for each of the four features that were introduced in the section, whereas each of the columns is used for the sublevels defined for the features that were introduced before. Thus, the matrix is gathering the different features that were define before (each one of the rows) with levels of each of the four features that were defined as of major importance considering what middleware is expected to do for the Smart Grid (the columns of the matrix, according to the different features that have been defined in the previous figures). The matrix has been represented in Figure 7.

If the matrix is used to describe a middleware proposal, each of its elements can be incorporated to an equation that

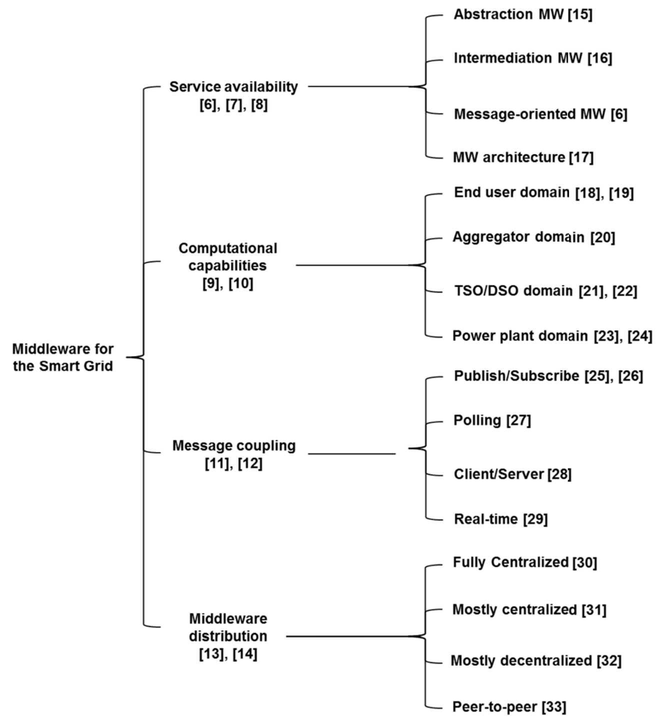

Fig. 6. Taxonomy with the most prominent features for middleware in the Smart Grid and their supporting references.

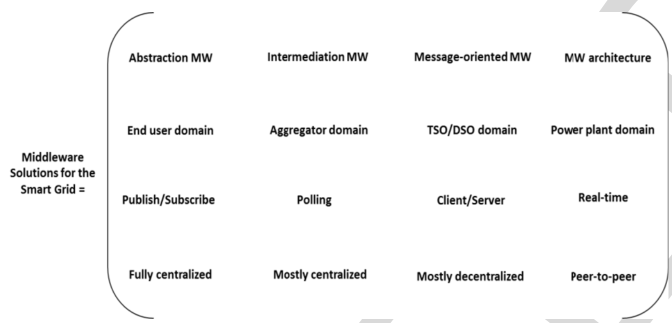

Fig. 7. Matrix for middleware in the Smart Grid.

will be used to represent the features involved in the middleware developments. For example, if a proposal is configured as being a middleware architecture that due to the information that has been provided has to be installed in the TSO/DSO domain, follows a Publish/Subscribe paradigm to interchange information and is present in several devices maintaining a strong hierarchical deployment, it can be described as:

Smart Grid Middleware = Service Availability (element no.3) + Computational Capabilities (element no. 2) + Message Coupling (element no. 0) + Middleware Distribution (element no. 1).

Consequently, it can be represented as:

$$SGM = SA(3) + CC(2) + MC(0) + MD(1)$$

Additionally, having an accurate idea of the specific aspects of a middleware proposal comes in handy to evaluate its strong points and weaknesses, and thus identify the open issues that can be found as common flaws present repeatedly.

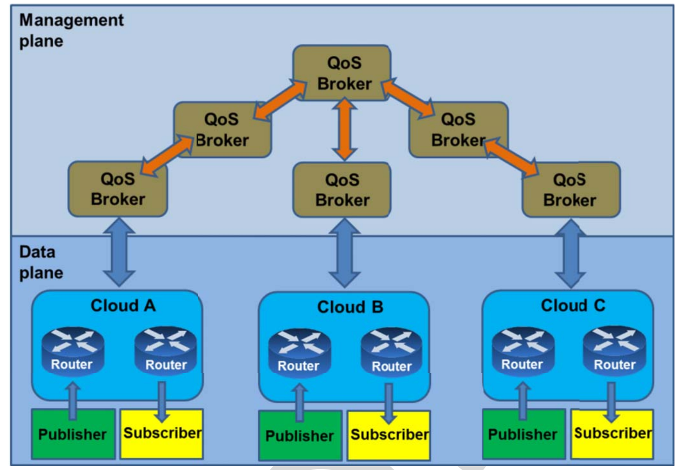

Fig. 8. GridStat structure, as depicted in [25].

IV. Study of Middleware Architectures for the Smart Grid

1. GridStat

Gjermundrod *et al.* describe in the proposal described in [34], how a framework can be built for Quality of Service-based data interchange using this framework as middleware for the Smart Grid. Middleware is quoted by the authors as "*a layer of software above the operating system that provides higher-level building blocks for programmers to use*", thus pointing at having a software layer for hardware abstraction by means of high level software components. One of the potential applications that the authors point out for their proposal is the distribution of time-synchronous and time-stamped information for Phasor Measurement Units [35] and the usage of the proposal as a way to support Remote Procedure Call (RPC) operations that will result in the utilization of Quality of Service semantic capabilities [36]. Considering the features that have been described, GridStat can be characterized as follows.

Service Availability: the authors have defined their proposal as an architecture that, as it can be seen in Figure 8, consists of two different levels referred to as *planes:* a *management plane*, which is responsible for fixing the procedures on how information is forwarded in the system, and a *data plane*, used for data transfers among the system (regardless of the location of publishers and subscribers) done by means of status routers that transfer the information from the suitable publisher to the chosen subscriber. Typically, data to be transferred will travel from a subscriber that has manifested its interest in a specific kind of information, and a publisher offering data to the network. However, it must be noted that the main purpose of the solution is data transfer among parties rather than providing a specific amount of services, so according to the characteristics that have been settled in the previous section, this middleware solution is better described as Message-Oriented Middleware.

Computational Capabilities: testing activities have been carried out considering the processors that can be found in a substation. Furthermore, data collection capabilities of substations are also taken into account, so it can be claimed that the solution is mostly targeted to be used in TSO and DSO pieces of equipment. Nevertheless, it is not said that it cannot be used anywhere else, as a Java implementation has been developed and Dell Power Edge 1750s servers were used as part of the hardware devoted to testing activities, which is hardware that could eventually be used by an aggregator or as part of a power plant.

Message Coupling: as far as the data plane is concerned, it is clearly stated in the proposal that it is aimed to use a Publish/Subscribe model for communications; publisher and subscriber entities are used to interchange information among the parties providing information and accessing to it. However, while Publish/Subscribe paradigm is the one that is most clearly aimed for, Client/Server-like communications are used in the management plane when commands are interchanged among the QoS brokers present at this level.

Middleware Distribution: this middleware solution has been conceived to be used in a rather decentralized manner, as data exchanges happen between several publishers and subscribers that are scattered in a certain area. The existence of a certain hierarchy among QoS brokers in the management plane makes the proposal fall under the category of mostly decentralized solutions, especially if it is taken into account that it is expected from the management plane that it will recalibrate the network depending on different power system configurations or communication network failures.

After analyzing the most prominent characteristics of this proposal, it can be described with the following middleware modelling equation if considering the matrix for middleware in the Smart Grid that was introduced in Section III:

$$SGM = SA(2) + CC(2) + MC(0) + MD(2) \quad (1)$$

Advantages of the Proposal: this piece of work puts forward a framework described in a very thorough way. Rather than offering just a theoretical framework where information is provided on how to build middleware, an implementation has been developed, along with performance results. Aside from that, the solution seems to be capable of running on hardware that does not require especially high computational resources, which eases its integration in the Smart Grid.

Disadvantages of the Proposal: GridStat has been conceived for data interchange instead of providing a specific amount of services for its end users, so there is not a clear collection of software components offering functionalities as it can be found in other middleware architectures. In addition to that, there are several key functionalities (ontologies for semantic capabilities, information models) that are not offered by the architecture. Lastly, although cyber security policies are claimed to be present in the proposal, it is not clearly stated how they are provided.

2. Service-Oriented Middleware for Smart Grid

According from the information that can be obtained from Zhou and Rodrigues [37], their solution has been conceived to integrate heterogeneous devices present in the Smart Grid and intends to offer a high level of software stability and sustainability. It is stated in the manuscript that service-oriented middleware is aimed to characterize several protocol stacks and scheduling schemes used to exploit the main features that user requests have. The authors put forward four fundamental principles for middleware design that they claim to be: a) clear specification of the relation between middleware functions and users' requests, b) support for computational complexity of heterogeneous applications, c) independence from the kinds of devices used and d) interoperability and portability. The proposal can be described with the following features.

Service Availability: the proposal is described as having the characteristics typical of a middleware architecture, since it has been clearly divided in three levels: *user part* (responsible for satisfying end users in terms of Quality of Service or Quality of Experience, and used to schedule flexibility for best QoS or providing quantifiable performance for the end user), *control part* (utilized for connectivity between the user part and the transmission layer and designed to deal with devices interoperating in the system and interchanging information between the former two entities) and *transmission layer* (used to offer services related to the Advanced Metering Infrastructure where the middleware solution is deployed). The user part offers functionalities related to bandwidth, applications and energy consumption, whereas the control part is focused on security, assignment and management. Last but not least, the transmission layer is bent on functionalities related to communication, generation and distribution. The overall appearance of these levels and the main services they can provide has been displayed in Figure 9.

Computational Capabilities: testing activities that have been described in the proposal by the authors show that there are four different scenarios where satisfactory Mean Option Score (MOS) has been obtained when comparing this proposal to Power-Aware Middleware (PAM) and Time-Driven Middleware (TDM) without worsening the performance of the solution. For each of the smart meters that were used for these testing activities, nodes with an ARM processor have been modelled as such. Therefore, end users or aggregators are the most likely actors to have this middleware solution installed as part of their equipment.

Message Coupling: while little information is given in the proposal, it is mentioned in the testing activities that request messages were transmitted, so it can be expected that answer were provided for these requests and the system would work under a Client/Server paradigm for information transfer.

Middleware Distribution: this proposal has been tested with several nodes and devices distributed in a certain area while still retaining some differentiated hierarchy in the functionalities that are performed. Consequently, it can be claimed that this is a mostly decentralized middleware solution due to the fact that it has been tested in simulations where distributed low capability devices are used.

As far as the matrix for middleware in the Smart Grid is concerned, the proposal can be described as:

$$SGM = SA(3) + CC(0||1) + MC(2) + MD(2) \quad (2)$$

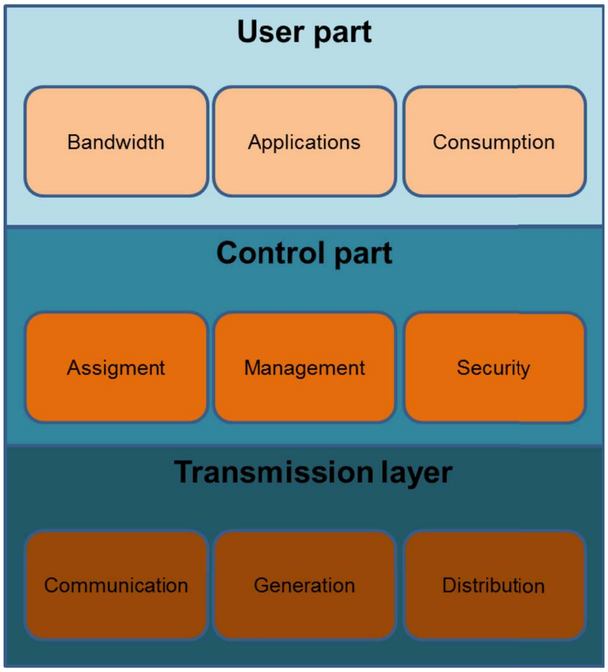

Fig. 9. Service-Oriented Middleware, as shown in [28].

Advantages of the Proposal: the proposal offers a collection of services that have been clearly described with the functionalities that they should offer, both within the middleware architecture and outside it. In addition to that, this middleware solution has been tested and shows an improvement in performance compared to other solutions. Last but not least, security measures are also mentioned to be part of the proposal (symmetric algorithms have been considered for this purpose).

Disadvantages of the Proposal: overall, the information that is provided in this proposal is oriented to high level functionalities, rather than specific ways to provide the services expected to be offered, so it might be difficult to fully port the content of this proposal to an actual Smart Grid deployment. Also, there are some elements that are confusing in the description offered for this proposal (for example, the Transmission Layer is described as part of the middleware, even though it is usually considered to be completely separated and below from it).

3. Ubiquitous Sensor Network Middleware (USN)

The proposal that has been conceived by Zaballos *et al.* [38] can be regarded as a way to adapt the framework given by the ITU ubiquitous sensor architecture. The manuscript that describes it mentions how that architecture is deemed as a network of Intelligent Electronic Devices, distributed generators, dispersed loads, sensors and smart meters. Among the technologies that become integrated under the same framework, this proposal also claims to integrate technologies of an array of backgrounds like Power Line Communication (PLC) or Worldwide Interoperability for Microwave Access (WiMAX). What is more, the authors mention that by using the framework provided by the Ubiquitous Sensor Network architecture and a Next Generation Network (NGN) as the backbone to deploy the proposal, full end-to-end integration of hardware devices in a distributed system can be achieved. The following information can be inferred from this piece of work.

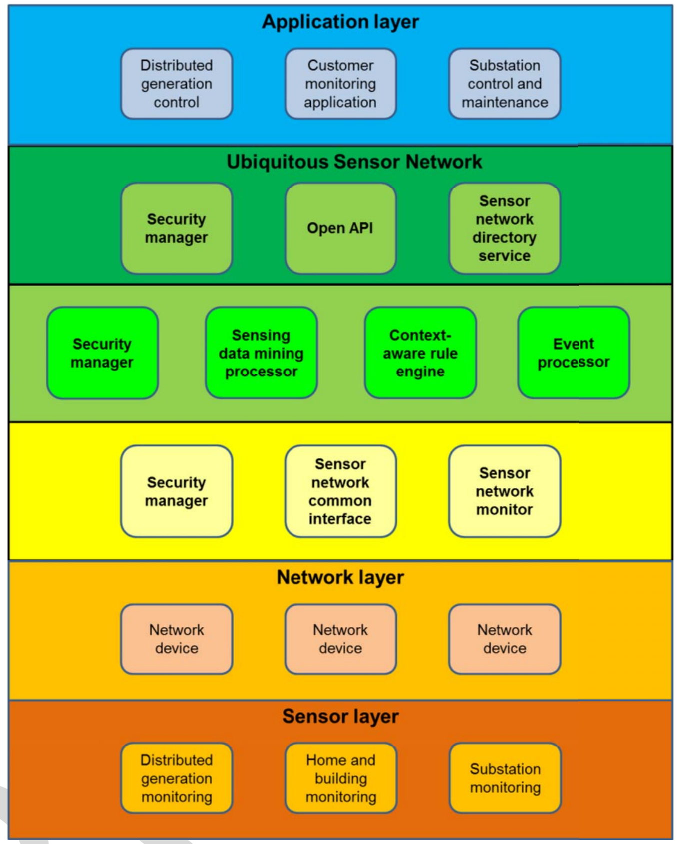

Fig. 10. Ubiquitous Sensor Network Middleware proposal, as described in [29].

Service Availability: services have been gathered as components from several levels within the proposal, so it can be regarded as a middleware architecture. As for the services that are put forward here, the most prominent ones are related to security (security manager), the underlying sensor network used in a deployment (sensor network common interface, sensor network directory service) and services linked to information management (sensing data mining processor, context-aware rule engine and event processor). Other layers that are present are the application layer (used for applications related to customer monitoring applications, substation control and maintenance and distributed generation control) network layer (involving network devices) and the sensor one (utilized for monitoring distributed generation, homes and/or buildings and substations). All these services have been shown in Figure 10.

Computational Capabilities: the proposal heavily emphasizes that sensor networks are the ones involved in the standards that are supported, so despite not having a strict equivalent to the elements of the Smart Grid, the least computationally capable devices present in it (that is, end user devices) should be the ones most likely to have the proposal installed. Nevertheless, as long as sensors are involved, the middleware solution can be used in any other facility, such as the hardware installed in the aggregator, TSO/DSO or the power plant.

Message Coupling: not only it is claimed by the authors of the proposal that the application level can be used for real-time purposes, but also it is mentioned that connection and authentication procedures would be performer under a Client/Server paradigm. Thus, it is inferred the real-time communications could be performed under a Client/Server communication, even though there is no explicit information about it.

Middleware Distribution: despite having scarce data about the location of the software components of the proposal, it is clear that a network layer is a prerequisite to have the middleware solution running, so the proposal can be regarded as decentralized to an extent. Thus, it has been considered as a mainly decentralized deployment.

Therefore, this proposal can be described with the following equation:

$$SGM = SA(3) + CC(0||1||2||3) + MC(3) + MD(2) \tag{3}$$

Advantages of the Proposal: the proposal offers a complete set of services in several differentiated layers where different functionalities are provided. Additionally, the middleware solution is either compatible or makes use of several well-established technologies like WiMAX or IEEE 802.15.4. It also mentions some prominent functions that middleware is responsible for (QoS, security, filtering) and how they become integrated in a single software layer.

Disadvantages of the Proposal: even though many services are mentioned, it is never said in an explicit manner the pieces of equipment where middleware would be installed, nor it is possible to have an idea from it judging from the performance tests carried out. Furthermore, there are several entities that have been described as part of the middleware but are usually regarded as outside from it and being located either above (applications) or below (hardware components of Wireless Sensor Networks).

4. OSHNet (Object-Based Middleware for Smart Home Network)

Park *et al.* [39] describe a middleware solution that stresses the importance between home devices and Smart Grid-related ones. As it happened with previous proposals, there are several levels used to separate different kinds of services: to begin with, the *application layer* is used for interaction with five Application Programming Interfaces (APIs) [40] in order to interact with higher levels. Additionally, there is a *library layer* utilized to offer data about the deployed home devices that contains several objects (control, function, streaming and status) and modules (object management, object discovery, connection management) for assistance in that task. Finally, a *network layer* is used for lower level connections and packet transfers among the distributed system where the middleware proposal is deployed onto. Considering the four different features that have been defined, the proposal can be characterized as follows.

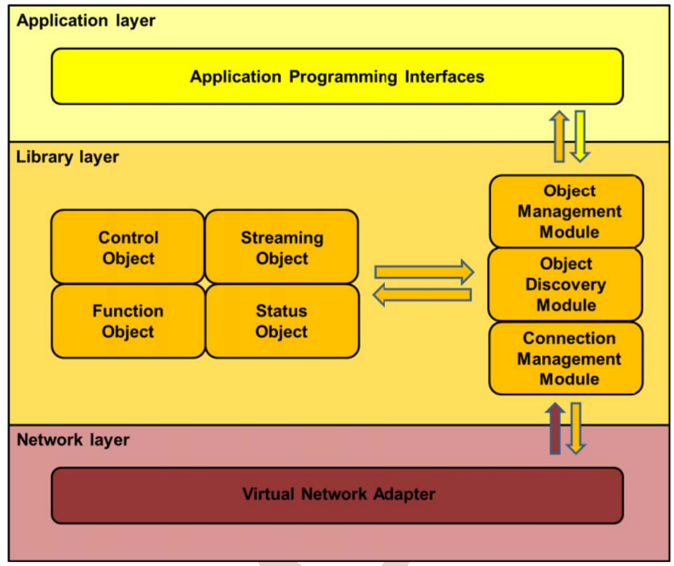

Fig. 11. OSHNet appearance, as described in [30].

Service Availability: the proposal shows services in several levels, so it can be considered to be a middleware architecture. Among the services present, the most important ones are the ones present in the library layer: *Control Object* (employed for control in neighboring home devices), *Streaming Object* (applied for the management of input and output data), *Function Object* (employed for function execution in home appliances) and *Status Object* (used to know about the status of the home devices that are available). Additionally, there are several modules that offer functionalities related to service invocation: *Object Management Module* (responsible for controlling the functionalities offered by the devices where the middleware proposal has been installed), *Object Discovery Module* (used to collect information regarding other home devices) and *Connection Management Module* (utilized for establishing, maintaining and terminating connections among devices). The appearance of these services can be seen in Figure 11.

Computational Capabilities: the middleware solution described here usually mentions home systems as the ones most likely to use the middleware solution, so it can be argued that the hardware aimed to use the proposal will be the one that can be found in the end users' dwellings, such as the Advanced Metering Infrastructure that is installed there. Testing activities described in the proposal show that virtual devices to be used in the proposal were a humidifier, a smartphone, a smart meter, a wind-powered generator and three laptops, so they reinforce the interpretation that can be done about computational capabilities.

Message Coupling: in spite of the lack of definite information about this topic, user interfaces are described as part of the middleware solution, so it can be assumed that there are clients to make requests and servers to provide information, hence resulting in a Client/Server paradigm.

Middleware Distribution: the authors of the proposal claim that the software used for the development of this proposal will be installed in Distributed Energy Resources, so the middleware solution must be decentralized enough in order to have it in the multiple devices where it is expected to work. Also, it is mentioned that there are several pieces of equipment that will be given ruling capabilities over the system, thus retaining some level of control for some hardware elements. Consequently, the proposal has been considered as a mostly decentralized one.

The proposal that has been described in this case can be modelled considering the matrix previously described as:

$$SGM = SA(3) + CC(0) + MC(2) + MD(2) \tag{4}$$

Advantages of the Proposal: this solution addresses several concerns involving services used for hardware interoperability. Testing activities have been carried out with several virtual devices to get a grasp on how the middleware solution will behave when it has to offer interoperability for heterogeneous hardware.

Disadvantages of the Proposal: the middleware solution that has been portrayed by the authors of this proposal use layers that are usually considered as outside middleware, such as the application and the network levels. What is more, the services that have been included in the middleware solution are basically referred to functionalities that are needed for their internal performance rather than services that will provide an external functionality, either for appliances integrated in the grid or for the application layer.

5. Meter Data Integration (MDI)

The proposal that has been put forward by Li *et al.* [40] offers a solution where information obtained from the Advanced Metering Infrastructure is included in a common deployment. The underlying idea is that MDI will be located between the hardware represented by the smart meters and the Distributed Management System (DMS). Other entities present in the middleware solution are the Meter Data Management System (MDMS), which operates as a data server, and a Meter Data Collector (MDC) that collects the data from the AMI. A remarkable aspect of this proposal is that it takes into account hardware characteristics that are present in smart meters used by large utility companies like Siemens or Pacific Gas & Electricity, so performance in real scenarios has been fully taken into account. The features that are represented in the proposal are as follows.

Service Availability: as other proposals, MDI has been represented as a multi-layered architecture with different functionalities included in each of the levels. The lowermost layer is used for typical hardware abstraction functionalities between the hardware elements present as part of the AMI and the higher middleware layers, whereas the uppermost one employs adaptors for the DMS that is used as part of the deployment. The intermediate layer is the one with most prominent elements: a temporal database is used to verify and translate the information gathered from the smart meters, whereas the Loosely Couple Event (LCE) infrastructure is used for message publication and subscription. Besides, there is a MDI monitor at this level monitoring the status of functional components present in the MDI layer. The overall appearance of the middleware solution has been included in Figure 12.

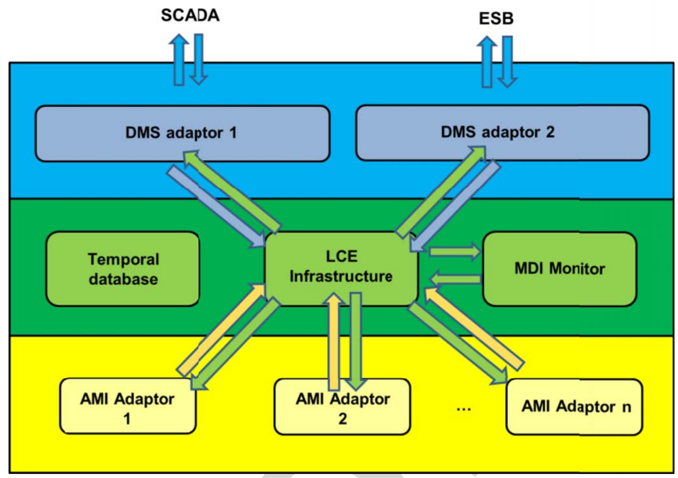

Fig. 12. Meter Data Integration proposal, as explained in [31].

Computational Capabilities: testing activities carried out with this proposal describe how two different pieces of equipment have been used to simulate smart meters present in a Smart Grid-like deployment. They were made by means of equipment using Windows Server 2003 and 2008 operating systems, so it can be claimed that they do not require extensive computational resources. Combining this fact with the name of the proposal and how it is aimed to be used with smart meters, it can be said that it is intended to be used by end users' hardware and no other entity in the Smart Grid.

Message Coupling: the middleware solution is aimed to provide loose coupling, as it is made clear by the presence of a software component intended for that purpose. In addition to that, it is mentioned through the proposal that a Publish/Subscribe paradigm is used ("*All functional components in the MDI layer are coordinated by publishing and/or subscribing messages to the LCE infrastructure*"), so the middleware solution has been classified following such paradigm.

Middleware Distribution: since the proposal is aimed to be used at the smart meter devices present in a deployment, it can be inferred that this is a mostly decentralized solution, due to the fact that it will be present in several devices that will require a higher-level entity to send information (usually, located at the aggregator or the DSO) for billing and information purposes.

This proposal can be defined by the following equation obtained from the description matrix used to encase the different levels of each of the four characteristics that were defined in Section II:

$$SGM = SA(3) + CC(0) + MC(0) + MD(1) \tag{5}$$

Advantages of the Proposal: The proposal has been targeted to use information and features related to actual smart meters. Furthermore, it is clearly stated as using a Publish/Subscribe paradigm and is expected to require small-sized computational resources, so the purpose and scope of the proposal can be accurately described and understood.

Disadvantages of the Proposal: The proposal does not go into great detail regarding how services can be implemented or the performance that implementations of the proposal are capable of providing. Plus, most of the services are solely focused on providing interoperability rather than any other functionality that can be expected to be used by the middleware to provide functionalities to other parts of the system such as security or semantics. Lastly, even though testing activities are welcome, they have been performed in a limited environment, rather than with actual devices or complex simulations with more devices.

6. IEC 61850 and DPWS Integration

The proposal conceived by Sucic *et al.* [41] merges two standards of common use in the Smart Grid at the electric and Information Communication Technologies parts. On the one hand, standard IEC 61850 is used as a communication model for functionalities as establishing requirements in device models or describing the language used for communications among substations [42]. On the other hand, Device Profile for Web Services can be used for interoperability purposes in constrained implementations of Web services [43]. The authors of the middleware solution argue that since IEC 61850 is defined as a platform-agnostic and software-agnostic standard (and makes use of an Abstract Communication Service Interface that is not associated to any middleware specification), Web services come in handy to create a middleware solution that will map enabled IEC 61850 communications. The mapping is referred to as Manufacturing Message Specification (MMS) which can in turn be also used for distributed power control transmission [44]. The proposal can be characterized by the following features.

Service Availability: the proposal is combining Web service elements usually present at the session and presentation layers from a layered architecture point of view. There are three layers that have been defined for the middleware solution, all devoted to providing Web services for applications in the Smart Grid. The one located at the lowest level is directly above the transport layer and formats information by means of the metadata XML schemas provided at this level. Additionally, Simple Object Access Protocol (SOAP) functionalities and Web Services Description Language (WSDL)-formatted data are also used. An intermediate level is used or Web service security, along with Web service policies (used to describe capabilities and limitations of available policies) and addressing (utilized as addressing mechanisms for Web services). Finally, the highest layer of the proposal contains functionalities for Web service discovery, metadata interchange and event management. Considering the different functionalities that DPWS is capable of providing, it can be claimed that the proposal is a middleware architecture. Figure 13 depicts the appearance of the several layers that make up the proposal.

Computational Capabilities: since most of the devices present in the Smart Grid are capable of using Web services from a computational point of view, hardware constrains play

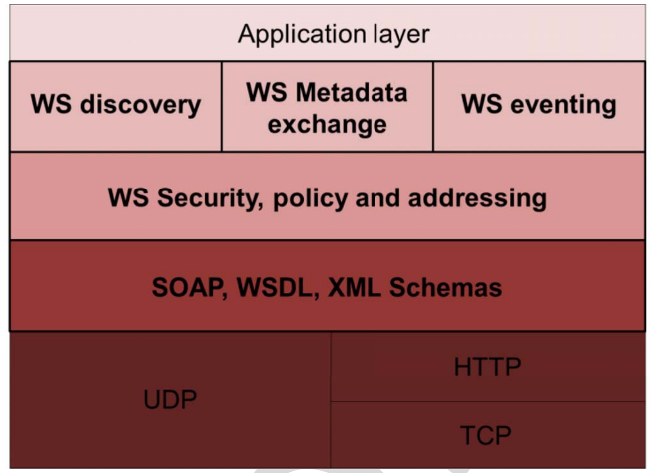

Fig. 13. Protocol stack of DPWS, as explained in [32].

a minor role in installing the proposal in different locations of the Smart Grid. The most suitable places to do so, though, can arguably be the TSO/DSO domain and the power plant one, as they are most useful there to gather information about all the system. In addition to that, DPWS makes use devices hosting the services (*hosting devices* and *hosted services*). Finally, the authors claim that Virtual Power Plants (VPP) can also be enabled by making use of the proposal.

Message Coupling: the middleware solution has been conceived to be used with Publish/Subscribe communications in several cases, and in fact the eventing component relies on that paradigm (as subscribers are listening to any event that might be published). Furthermore, the authors of the proposal say that ACSI runs with a Report Control Block that needs a Publish/Subscribe model for its correct performance.

Middleware Distribution: although there is a certain level of hierarchy that can be inferred from the proposal (power plants are aimed as one of the likely entities to have the proposal installed, and there is a significant amount of electricity coming from them to the TSO grid and the end users, especially if they are not equipped with DERs), the nature of Web services makes desirable using them in a plethora of components that are distributed, so it must be regarded as a mostly decentralized middleware architecture.

Overall, this proposal can be described as:

$$SGM = SA(3) + CC(2||3) + MC(0) + MD(2) \tag{6}$$

Advantages of the Proposal: The proposal makes open mentions about how semantic capabilities can be used, which is quite an improvement over many other ones where they are not considered at all. What is more, VPPs have also been taken into account for the proposal and security is also given a specific component in the middleware solution.

Disadvantages of the Proposal: The authors have not presented information regarding testing activities so it is hard to figure out the performance of the proposal. Also, it is hard to tell how hardware abstraction is provided in the proposal, as DPWS is mostly focused on high levels of layered software architectures and the mechanisms used by ACSI are not described.

7. Intelligent Agents Platform

García *et al.* [45] suggest their own solution for device interoperability at the data level focused on hardware for both the Smart Grid and other application domains such as Home Area Network devices. The proposal is referred to as Intelligent Agents Platform (IAP) due to the fact that a platform is used for data interchanges between entities. Under this proposal, the hardware devices present in a deployment would be managed by IAP Mediation Devices, whereas the management required for the elements that belong to the deployment is done via Integrated Network Management (INMS) functionalities. A major aspect of the proposal is that it makes use of an Enterprise Service Bus (ESB) to encase all the functionalities that have been included in the proposal. An ESB is a model for software architectures used for data interchange that makes possible the transfer of information among applications of distributed and different characteristics regarding implementation. Also, the usage of an ESB usually hints that there will be a collection of services that are used for the benefit of system components that are outside middleware. As far the proposal itself is concerned, it can be defined by the following features.

Service Availability: there are several software components encasing functionalities that are provided as services, so the proposal can be considered a middleware architecture. As in several other cases, there are three different levels that have been created in order to contain the services the middleware solution is made of: a) two management layers employing internal buses for information interchange (referred to as *Network Mediation Layer* and *Management Application Layer*) and b) and intermediate one connecting the management layers (Middleware Communication Services) that depending on the requirements of the operational models might or might not be present. The main functionality of the Network Mediation Layer is processing the information transferred through the whole system that has been set. Additionally, there are appliances named IAP Mediation Devices (MDs) that make use of the network mediation layer for control activities. At the same time, the Management Application Layer is responsible for the usage of application locks meeting an end user functionality (reporting engine, task scheduler, data handling, etc.). Finally, Middleware communication services are useful to connect one data layer with the other one for data transport between the mediation system and the back end of the applications. The location of the software components that are present in the proposal can be seen in Figure 14.

Computational Capabilities: according to the authors, the middleware proposal can has been tested several times in differing application domains. It is also claimed that Customer Premises Equipment was utilized for a deployment where data was transferred by means of an IP network. However, there is little data regarding how information was transferred. It has been presumed by the authors of this manuscript that simulation data was used in order to measure the performance of the proposal, as it is claimed that each Mediation Device controls one hundred concentrators, thus obtaining a total of ten thousand AMIs to be managed. Therefore, it can be argued that since the proposal is aimed at controlling smart meters, it would be expected to be installed in the Aggregator or the TSO/DSO infrastructure.

Message Coupling: it is cited by the authors of the proposal that it is capable of transferring information both as real-time event collection and as Publish/Subscribe mechanisms as utilized by Intelligent Agents Platform as a way to implement test activities. In addition to that, polling-like communications performer at the concentrators used for tests are also mentioned. Lastly, peer-to-peer data transfers are also present in the middleware solution, thus having each of the message coupling levels established in Section II of the manuscript.

Middleware Distribution: as it happened in previous cases, scarce data is present about how distributed the proposal is. Nevertheless, it can be argued that since Mediation Devices and the Intelligent Agents Platform are running in several devices rather than in a centralize power plant, along with the fact that smart meters are managed by the software components of the middleware solution, this is a mostly decentralized middleware.

The proposal can be described with the following equation:

$$SGM = SA(3) + CC(0||1||2||3) + MC(0) + MD(2) \quad (7)$$

Advantages of the Proposal: The proposal seems well suited for the purposes of middleware in a Smart Grid, as it offers a significant degree of decentralization since it is able to transfer data of very different nature. Furthermore, the usage of an ESB guarantees that there will be a collection of services encased in the middleware solution, which is consistent with what is expected from middleware.

Disadvantages of the Proposal: despite using an ESB, the amount of services offered by this middleware solution seems lower than in other proposals. Besides, information about the performance of the system, along with how many of its features are provided, is missing. Last but not least, there is no description of how functionalities of critical importance, like hardware abstraction or security, are offered by the proposal.

8. Self-Organizing Smart Grid Services

Awad and German put forward their own ideas for a middleware solution for the application domain of the Smart Grid in [46] and [47]. According to their proposal, there are several metrics that have been defined as *degrees*, which are employed to quantify the features that should be present in a specific middleware development and the extent they should be present. The degrees that are described in the proposal are a) *degree of robustness* (used to assess adaptability of self-organizing devices), b) *scalability* (checks if information can be created by means of local messages), c) *flexibility* (offers redundancy on order to avoid single points of failure in the deployment), d) *emergence* (a phenomenon to be witnessed at a macro level), e) *target orientation* (how nodes create their own data from an initial state), f) *reliability* (capability of self-organizing devices to find alternative solutions when an issue appears, as route unavailability) and g) *parallelism* (ability of

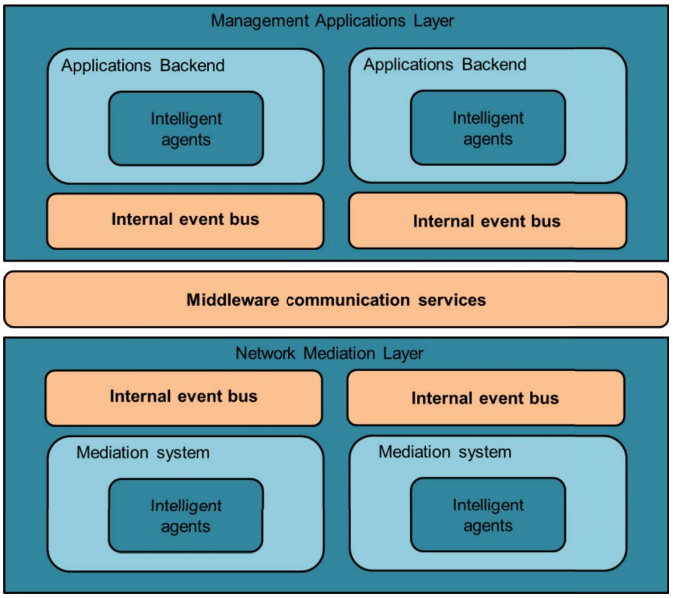

Fig. 14. G. Intelligent Agents Platform proposal, as depicted in [36].

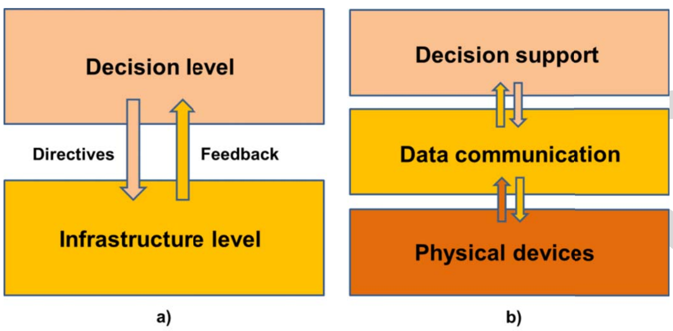

Fig. 15. Solution structure (a) and main levels of the proposal (b), as described in [37].

a service to join or leave the deployment simultaneously from different sides). This proposal can be evaluated as follows.

Service Availability: the proposal is mostly devoted to services that can be offered in the context of the Smart Grid rather than the middleware as a separated software entity, as it is regarded to be located in one of the two levels shown in Figure 15 (a). There, it can be observed that there is an infrastructure level used to provide feedback employed to take decisions, along with a decision level utilized for data reception, supervision and control. Those levels presented there resemble the solution structure provided in Figure 15 (b). In this latter situation, decision support is performed at the decision level and data communication is combined with physical devices that match the infrastructure event to an extent. The middleware solution included in this proposal is expected to deal with several functionalities, like aggregation, filtering, data routing and replication. Contrary to what is presented in other proposals, middleware is regarded as a mere way to guarantee communications at the data level at the infrastructure side. Thus, it has been considered as an abstraction middleware.

Computational Capabilities: although no explicit mentions are done about hardware devices to be used, it can be inferred from the provided information that the infrastructure level is roughly equivalent to Advanced Metering Infrastructure and the decision level can be placed at the aggregator, since it is used to control hardware devices located at the very end of the deployment and are able to send commands.

Message Coupling: it is explicitly mentioned in the proposal that real-time communications can be provided for data transfers. No other mentions are done to other kinds of communications.

Middleware Distribution: the authors of this solution and its corresponding middleware layer disagree with middleware developments that tend to be centralized, and mention how all communication nodes have the same importance in terms of data transfers. Despite the exact degree of middleware distribution that is given by the proposal is not clearly mentioned by the authors, it can be argued that it is a peer-to-peer motivated one, as it is the most preferred structure for network communications.

The proposal can be described by using the matrix for middleware in the Smart Grid, resulting in:

$$SGM = SA(0) + CC(0||1) + MC(3) + MD(3) \quad (8)$$

Advantages of the Proposal: The proposal makes use of a fully decentralized way to interchange information at the data level among different software components while abstracting hardware heterogeneity among them.

Disadvantages of the Proposal: in spite of making clear where middleware is located, there is little information about how it is used when it is deployed. What is more, testing activities done on the middleware proposal are scarce, or few data have been given about them. Lastly, there are no major services provided by middleware that are offered in other proposals (securitization, semantic features).

9. Secure Decentralized Data-Centric Information Infrastructure

The middleware solution that is proposed by Kim *et al.* [47] highlights the importance of having a framework for a decentralized and distributed system that can be ported to the Smart Grid. It is claimed by the authors that the middleware solution takes into account issues like latency, real-time events, distributed data resources and security. There are Information and Communication Technologies infrastructures that make use of the Internet Protocol as the underlying way for packet transfer at the network level. Service securitization is also provided and, according to the authors of the proposal, the Common Information Model is implemented as well so as to interchange information among Energy and Distributed Management Systems (referred to with their acronyms, EMSs and DMSs). As a consequence of security implementation, it has been assumed that devices available in the deployment can deal with symmetric-key operations that establish secure channels (public-key operations are usually far more costly regarding time and performance). Considering the features introduced in the previous section, the features that have been described are as follows.

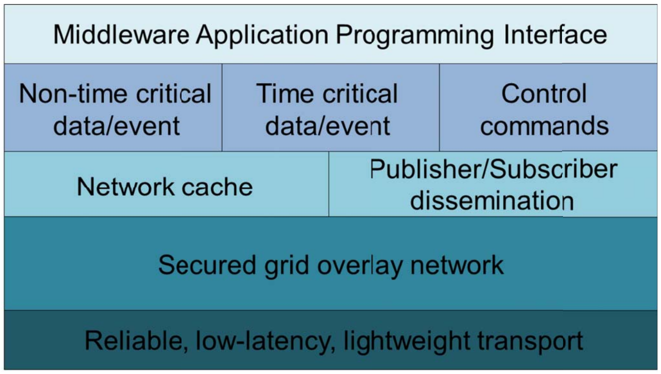

Fig. 16. Secure Decentralized Data-Centric Information Infrastructure, as described in [38].

Service Availability: the proposal has been conceived as a group of services organized in separated layers. Therefore, it can be considered as a middleware architecture. Among the levels that have been conceived for this proposal are: a) *power applications* (located over the middleware layer and consisting of applications to be employed by end users), b) *Middleware Application Programming Interface* (describes how the middleware solution can be accessed from the application layer and the functionalities that middleware provides to it), c) services offered for event management (non-time critical and time critical data/event components and control commands), d) software components for networking and distributed information transfers (*network cache* and *Publisher/Subscriber dissemination*), e) a *secured grid overlay network* (used for network communications in unicast, multicast and broadcast modes) and f) *reliable, low-latency, lightweight transport* protocols (for information transport). Overall, the appearance of the proposal and all its elements has been included in Figure 16.

Computational Capabilities: the authors of the proposal claim that their proposal is data-centric rather than host-centric, so hardware must be taken into account just for the sake of having the software components installed. Considering the distributed nature of all the elements surrounding and making use of the middleware solution, end users, the aggregator or TSO/DSO infrastructure can be used to include the proposal.

Message Coupling: one of the proposal software components makes use of Publish/Subscribe information dissemination, so it can be stated that it is the main style of data transfers among the elements of the proposal. However, real-time is also enabled by means of the components that handle events; the authors of the middleware solution claim that the proposal can be offered by using a Real Time Protocol as well.

Middleware Distribution: it can be argued that the middleware solution is a mostly decentralized one, as it makes use of network elements present in a distributed system but also does not provide any information about a peer-to-peer potential nature of the proposed solution.

According to the matrix that was defined previously, this middleware proposal can be defined as:

$$SGM = SA(3) + CC(0||1||2) + MC(0||3) + MD(2) \quad (9)$$

Advantages of the Proposal: The proposal is strongly influenced by the features that are present in any distributed system, so its portability to other solutions is manageable. Implementation and deployment seem easy enough as well, due to the fact that networking and securitization capabilities are guaranteed by using popular technologies. Alas, the availability of an Application Programming Interface (API) makes possible accessing the middleware in an accurate way in order to request services from it.

Disadvantages of the Proposal: there are several elements included in the proposal that fall beyond the scope of middleware, such as applications or networking infrastructure. Also, there are some other major services (semantic capabilities, context awareness) that have not been included in the proposal. Lastly, the implementation that has been carried out seems more aimed to including additional functionalities that have been built on top of the networking layer instead of developing a separate, distributed software layer for hardware heterogeneity abstraction.

10. A Cloud Optimization Perspective

Fang *et al.* describe in [48] the main features that a middleware solution should have, according to their ideas. From their point of view, a cloud computing-based infrastructure is the most suitable one to provide services in a distributed manner. Indeed, cloud computing developments are extremely popular for distributed and Cyber-Physical Systems; they are offered by large companies such as Amazon (Amazon Web Services, AWS [49]) and Microsoft (Microsoft Azure [50]) to develop and store software applications. In the authors opinion, by enabling cloud computing for the Smart Grid there are four objectives that can be obtained: a) it improves information integration due to the fact that it avoids isolated data or what the authors refer to as "islands of information", b) it can have outsourced tasks involving information management, therefore resulting in a less complex system, c) it can make the duties of Distributed Energy Generation parties easier and d) it fits high information processing requirements for the Smart Grid. If the four previously defined features are taken into account, the proposal can be described in the following manner.

Service Availability: the proposal has been regarded by the authors of this manuscript as a middleware architecture. This has been done because the domains that encircle the applications can be roughly regarded as layers or levels containing software components, even though most of them are not piled but encasing software services. These domains are: the *Smart Grid domain* (consisting of seven different smaller domains characterized as different services playing a major role in the Smart Grid: Service Providers, Operations, Markets, Bulk Generation, Transmission, Distribution, Customers), the *network domain* (employed for networks and communication infrastructure), the *cloud domain* (used for storage purposes) and the *broker domain* (used for mediation between the requests done by the users of the Smart Grid domain and the cloud services available to serve them). The location of all the software components of the proposal has been established as in Figure 17.

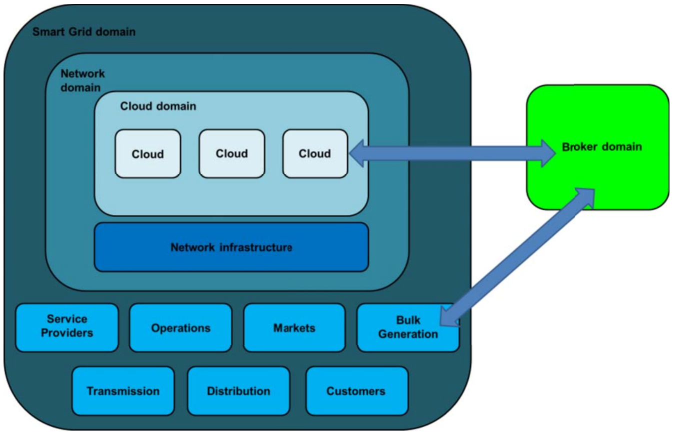

Fig. 17. Cloud optimization perspective, as shown in [39].

Computational Capabilities: this feature is relying on constrains and possibilities that cloud computing offers as infrastructure. Due to the fact that the authors claim the cloud being able to separate the ICT-related functionalities of the Smart Grid from the more hardware-based ones, any appliance capable of running the software required for the proposal (for example, the CPLEX Studio tool from IBM, is mentioned as one of them) will be able to store the required software. Thus, it has been deemed suitable to include all possible hardware options for this part of the proposal characterization (as it could be included in servers or Personal Computer-like appliances present in end users' equipment, aggregator hardware, TSO/DSO domains or power plant facilities).

Message Coupling: the proposal does not mention a specific way to interchange information among the hardware components of a Smart Grid-like deployment. Nevertheless, at least it can be assumed that cloud computing infrastructures are able to provide information when it is requested to them as real-time information, thus making possible this form of communication, along with a Publish/Subscribe paradigm (where data obtained from the Smart Grid can also be kept in a repository until an entity subscribed to the data provided by a publisher requests it).

Middleware Distribution: cloud computing infrastructure can be conceived as a mostly decentralized system due to the fact that it offers services to be included in a number of devices, but there is still a hierarchy that rules them (for example, the broker domain is of more centralized nature that all the others).

The middleware proposal that has been described in this case is more accurately described as:

$$SGM = SA(3) + CC(0||1||2||3) + MC(0||3) + MD(2) \tag{10}$$

Advantages of the Proposal: the proposal offers a very accurate description of the appearance of the services that must be provided by a distributed system based on cloud computing. The fact that there is a distinction between the ICT-based services and he ones relying on the power grid is appealing due to the fact of easing the development of services related to both areas from an implementation point of view. Finally, major services as security are included in the proposal as well, with performance tests assessing how well they work.

Disadvantages of the Proposal: the inclusion of an API would have been useful to have a good grasp on how to access the infrastructure provided by the authors of the proposal. Furthermore, even though commercial solutions have been built with the same kind of services that are described in this case (for instance, Amazon Simple Storage Service is used as a way to work with other cloud platforms [51]), it is not clear how they are built in case of the described solution. Lastly, there is no information on how messages are interchanged among interested parties in this middleware solution.

11. KT Smart Grid Architecture and Open Platform

The proposal that is explained in this case is about a commercial solution that makes use of an energy management platform developed by KT (former Korea Telecom) employees Lee *et al.* [52]. Functionalities offered by a Service Oriented Architecture have been taken into account, as well as other disciplines as intelligent agents and business process management. The new services that have to be included so as they become integrated as part of the Smart Grid (Electric Vehicles, Distributed Energy Resources, Demand Side Management, Demand Response, etc.) have been considered in this proposal. This middleware solution is offered as an open source development, so scalability and service availability can be updated and ported depending on the particular needs of a deployment. The proposal has been characterized as follows.

Service Availability: considering that the main components of this middleware proposal have been divided in three different layers, the solution presented by KT has been deemed as a middleware architecture. There are several elements that have been included in the architecture: the highest level has been named Customer Energy Management Systems (CEMS) that encases management capabilities for home dwellers (Home Energy Management System, HEMS). The second one relies on a data base involving information about customers, metadata collected from the system or energy usage. The third level is used for the management of the Demand Response service (Demand Respond Management System, DRMS), renewable energies (Renewable Energy Management System, REMS), business operations (Business Support System, BSS) and smart metering information (Metering Data Management System, MDMS). In addition to this, a low level interface has been added with the purpose of connecting Smart Grid appliances (Supervisory Control And Data Acquisition systems or SCADAs, power panels, Advanced Metering Infrastructure). The overall appearance of the architecture has been described in Figure 18.

Computational Capabilities: considering the platform itself, it is expected that it will have several devices with different amounts of content present in them. Information will be gathered from SCADAs or AMIs, it could be placed in a device that is outside them (aggregator, TSO/DSO domain), so end users' equipment, aggregator and TSO/DSO domains have

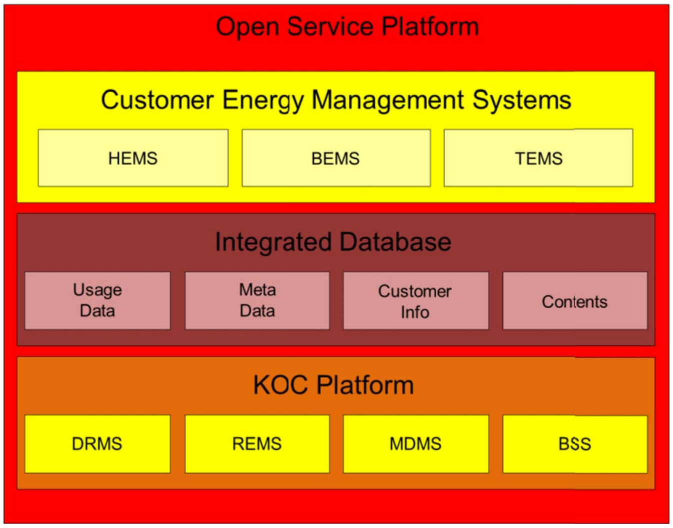

Fig. 18. KT Smart Grid Architecture, as shown in [43].

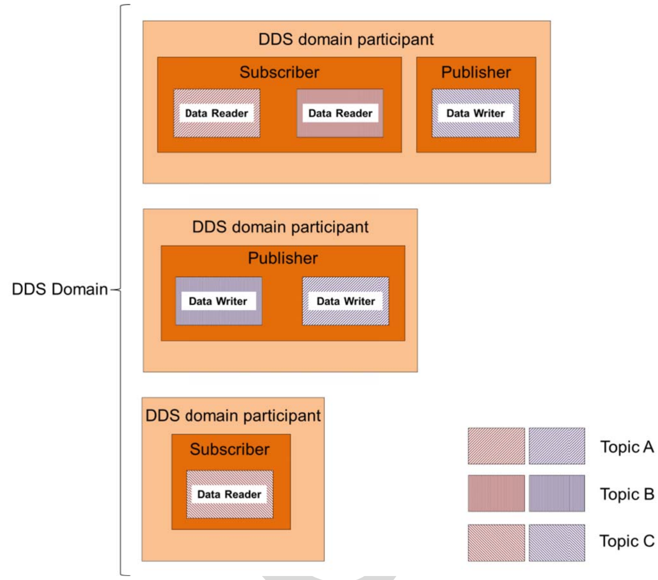

Fig. 19. Smart microgrid monitoring with DDS depiction, as described in [44].

been chosen as the most likely ones to have the proposal included in them.

Message Coupling: the data are expected to be collected and distributed in a real-time fashion. Aside from that, little information is offered on how to transfer data among the entities surrounding the proposal.

Middleware Distribution: the authors of the proposal claim that it will be installed in several devices belonging to the locations where they are needed. However, since some of those appliances will feed data to the system, the proposal has been considered a mostly decentralized one.

This proposal can also be described as:

$$SGM = SA(3) + CC(1||2||3) + MC(0) + MD(2) \quad (11)$$

Advantages of the Proposal: this proposal has been tested in a real deployment where data regarding energy consumption or energy flow was provided to end users. Therefore, assessments of electricity usage and user information have been strongly considered for this proposal. Also, having the platform as an open development is a positive feature of the platform due to the fact that it can be enhanced and extended considering the specific needs of a deployment.

Disadvantages of the Proposal: the how data is sent from one side of the communications to the other is not thoroughly described in the proposal. Furthermore, the end users that have been considered are mere consumers, rather than potential prosumers than may be willing to provide their own power supply to the grid. There some major services as security that have not been included in the proposal. Lastly, information regarding API or application layer access is not offered either.

12. Smart Microgrid Monitoring With DDS

The proposal that has been put forward by the authors ha a fundamental difference with the ones that have been presented before because it makes use of a standard of the Object Management Group (OMG) called Data Distribution Service (DDS) aimed to offer interoperability in distributed and Cyber-Physical Systems [53]. DDS defines a software layer that can be ported to a system such as the Smart Grid so that it will offer interoperability for hardware at the data level, as if it was a middleware solution. The DDS specification has been divided in two different levels, where one is used for Data-Centric Publish/Subscribe communications (DCPS) and the other one for compatibility among different versions of DDS distributions and real-time communications (Real Time Publish Subscriber, RTPS). The standard defines all the characteristics require to understand the role of the components and how they are related to each other. Also, how a Platform Independent Model (PIM) is established as a generalist description of the standard, and how it can be further specified for standardized communications by having a Platform Specific Model (PSM) is described as well.

DDS makes use of several concepts in order to define the roles undertaken by each of the parties involved in the communications. Among them, three are of major importance: topics, domains and domain participants. A *topic* is a definition for an association of participants in a data transfer specified and distinguished from others by means of several characteristics (topic type, topic identifier and topic name). At the same time, a *domain* is a data space that is used to comprehend a logical network for the participants in the communications [54], where the entities referred to as *domain participants* publish information of interest for the subscribers.

The middleware proposal that is put forward by the authors makes use of the previous concepts, in the sense that it has been built from scratch just using the functionalities that DDS is capable of providing. In this sense, there are several domain participants within a single DDS Domain, where publishers are offering information to the subscribers among the domain participants depending on the topic they are participating in. The appearance of the proposal that has been put forward has been depicted in Figure 19.

Service Availability: the proposal has been designed as a way to transfer messages collecting information from devices present in a microgrid. The usage of DCPS also ensures that an API can be used by the high level applications as a way to retrieve data, but since there are no services encased in the proposal offering functionalities to external actors of the system (security or semantics), the proposal has been considered to be a Message-Oriented Middleware.

Computational Capabilities: the information regarding the kind of devices that should is scarce, but it can be said that, according to the authors of the proposal, middleware is used to obtain information from devices like wind turbines, so it can be expected to have the middleware running in the end users' equipment, along with the one present in the aggregator or the management functionalities required in the TSO/DSO part.

Message Coupling: the paradigm of Publish/Subscribe is of major importance for the architecture that has been conceived by the authors of the proposal, as DDS itself is strongly linked to this paradigm. The standard will make possible that the publisher implements a data writer, while the subscriber will make use of a data reader to gather the information published by the other part of the communications. In addition to that, real-time data transfers are also implemented by the proposal due to the same reason: DDS uses a layer for interoperability that implements real-time capabilities.

Middleware Distribution: the proposal is expected to be installed in several devices, as its components are located in different pieces of hardware. Then again, the DDS standard (and by proxy, the proposal put forward by its authors) keeps a certain hierarchy in the elements that are involved in data transfers (as their functionalities are using differentiated software components). Thus, the proposal has been considered as a mostly decentralized one.

Considering the features present in this proposal, it can also be depicted as:

$$SGM = SA(2) + CC(0||1||2) + MC(0||3) + MD(2) \tag{12}$$

Advantages of the Proposal: the DDS standard can be used with relative ease in distributed, Cyber-Physical Systems as a way to implement a middleware solution. Furthermore, it can be easily ported from one development to another one depending on the needs of a specific project. Different kinds of communications (real-time, Publish/Subscribe) can be supported by the system.

Disadvantages of the Proposal: the fact that the proposal is based on DDS makes possible to implement a compelling middleware solution, but it does not provide any facility related to the Smart Grid by itself, so many Smart Grid-related details must be implemented from scratch. As far as the proposal built on top of it is concerned, no additional, major services that could be obtained from a middleware architecture can be provided in this case, and more information could have been provided regarding the devices that could be used to have the middleware solution installed.

13. ETSI M2M

Lu *et al.* have chosen to define a proposal [55] that relies on a collection of standards for Machine-to-Machine (M2M) communications described by the European Telecommunications Standards Institute (ETSI, [56]) for it to be ported to the Smart Grid. While ETSI is more focused on the Internet of Things than other areas of knowledge, the Smart Grid can still be related to it due to the distributed nature of both kinds of systems, with a number of similar challenges such as security, scalability or interoperability, despite having some applications that are specific to the nature of the Smart Grid (for example, Demand Response). The design that has been made for ETSI M2M has Service Capabilities (SCs) as one of the pivotal ideas that make possible offering the functionalities required by the applications located in the upper, application-based level. SCs that are mentioned in this proposal are: Remote Entity Management, Telco Operator Exposure, Application Enablement or Interworking Proxy.

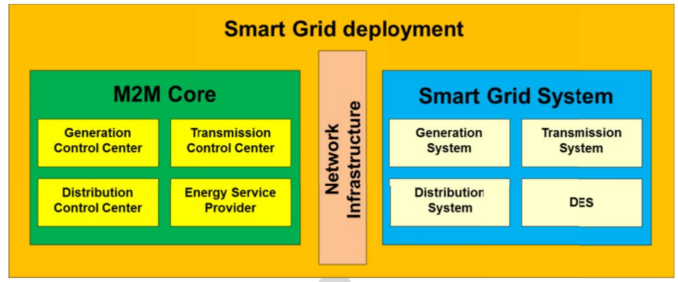

Fig. 20. M. ETSI M2M proposal, as described in [46].

Service Availability: the authors of the proposal have conceived it as a middleware architecture with several services in it. The Service Capabilities that are mentioned in the proposal are claimed to be portable for different kinds of hardware, without requiring a specific underlying technology. A useful addition that this proposal offers is the inclusion of an open source Application Programming Interface for application access to the middleware solution. There are two differentiated kinds of functionalities that are present in the middleware solution. On the one hand, there is a group of functionalities gathered as M2M Core ones: a) *Generation Control Center*, b) *Transmission Control Center*, c) *Distribution Control Center* and d) *Energy Service Provider*. On the other hand, the Smart Grid System mirrors these previous functionalities as systems rather than control centers (generation System, Transmission System, Distribution System) while at the same time taking into account the Distributed Energy Resources that can be offered to the system. Security and device management have also been considered for the proposal. The location of the different entities of the proposal has been displayed in Figure 20.

Computational Capabilities: the authors of the proposal have made clear that SCs can be present in M2M communication cores or gateways, which are equivalent in terms of computational capabilities to PCs or servers. Also, the proposal has been primarily conceived for its usage in IoT-related scenarios, so it can be expected that hardware constrains are not particularly troublesome. Taking into account all these facts, the proposal can be installed in every part of a Smart Grid-related development.

Message Coupling: even though there is little information on how messages are transferred in the proposal, real-time automated responses are mentioned by the authors of the middleware solution. Besides, the idea of having servers with available information is present during the description of the proposal (M2M are explicitly mentioned), so Client/Server communications can also be regarded as suitable in this case. Finally, elements used under a Publish/Subscribe paradigm like brokers are not mentioned, so this latter case seems unlikely to be used.

Middleware Distribution: as it happens with distributed, Cyber-Physical Systems in general, and IoT-like proposals in particular, this is a mostly decentralize middleware architecture. Interestingly enough, peer-to-peer communications would also be possible, as it is mentioned that there are several pieces of equipment communicating among them without the intervention of any user or application that provides a prominent hierarchy or management.

The middleware solution can also be described with the following equation:

$$SGM = SA(3) + CC(0||1||2||3) + MC(2) + MD(2||3) \tag{13}$$

Advantages of the Proposal: this middleware solution offers a way to access to its services via an open API that makes clear how to invoke services and functionalities. In addition to that, prototyping activities have also been detailed for each of the features that are of major importance for the authors (security, device management, Demand Response, interoperability and scalability).

Disadvantages of the Proposal: the proposal fails to provide any information of the required actions for it to be ported from an IoT deployment to a Smart Grid-based one. Information about how services are provided could also be more complete. Lastly, message transfer operations among the system are not clearly described in the paper that has been found.

14. Smart Middleware Device for Smart Grid Integration

Oliveira *et al.* [57] describe how middleware can be encased as another software component in only one appliance especially built for Smart Grid scenarios. The authors claim that integration between middleware and already standardized protocols like Modbus (a standard oriented to industrial applications) that needs specific gateways when working in cooperation with other elements of the grid. The proposal that is described in this piece of work describes one of these gateways, referred to as Smart Middleware Device, consisting of software components used in protocol translations, as well as data flow characteristics. The device itself will be used to interconnect the ICT and electricity elements of the Smart Grid, having the power stations at one side of the communications and the ICT infrastructure used to establish communications through its suitable locations (particularly, routers at the network layer). Considering the features that have been previously defined, the proposal can be characterized as follows.

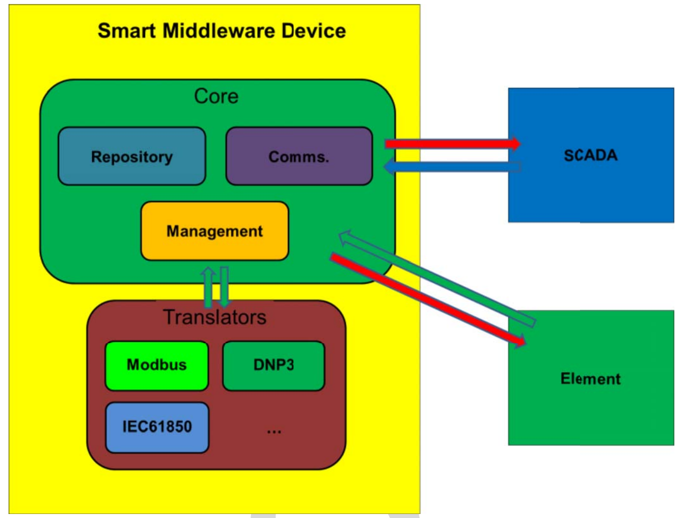

Fig. 21. Device for Smart Grid Integration, as depicted in [48].

Service Availability: basically, the proposal has been conceived as a middleware architecture that is installed in a single device. There is a collection of services offered within this proposal as two different groups that interact with each other: the core and the translators. *Core* components are utilized for the typical functionalities related to information transfer in the Smart Grid. In this way, when a query is done to the system, its answer will be stored in a *repository*, whereas another part of the core will deal with the *communications* with external elements for data gathering (such as SCADAs) and data *management* when information is interchanged with the group of translator functionalities. These latter ones will be used for protocol data translation between the elements involved in information transfer: Modbus, IEC 61850 and Distributed Network Protocol are mentioned as the protocols that can be translated. The appearance of the proposal has been described in Figure 21.

Computational Capabilities: the middleware architecture is strongly linked to a specific device in this proposal. The authors mention that the middleware solution has been installed as a service running in a machine with a Linux, Berkeley Software Distribution (BSD)-like operating system. With these features alone it could be included at any location of a Smart grid deployment, but since protocol translation functionalities have been enabled, it seems more useful to have the middleware solution running as part of the TSO/DSO infrastructure or even at the aggregator.

Message Coupling: the authors mention the proposal as being working under a Client/Server paradigm. Also, they claim that real-time information was received from a Smart Grid scenario, with Quality of Service parameters able to trigger alarms or actions to be carried out.

Middleware Distribution: the proposal has been installed in a single hardware device that acts as a gateway within the system. Therefore, it must be considered as a fully centralized middleware solution used for industrial protocol translation and data transfer.

The middleware solution has been defined with the next equation, according to the previously presented matrix:

$$SGM = SA(3) + CC(1||2) + MC(3) + MD(0) \quad (14)$$

Advantages of the Proposal: This middleware solution is able to become integrated with other services such as General Packet Radio Service (GPRS) in a single device. Furthermore, testing activities have been reported as satisfactory, and this middleware solution has been able to port multiple protocol formats of widespread developments, which can be regarded as a major achievement.

Disadvantages of the Proposal: unlike all the other proposals that have been found, this middleware solution works as a collection of software functionalities located in a single device. From the authors of this survey on middleware for the Smart Grid, that concept may be prone to several challenges: in case of failure of the device where the proposal is installed, no middleware will be available for the system. In addition to that, information on how the implementation works have been done to include the middleware in that device is scarce. Another issue is that having a single device with the middleware components seems to contradict the idea of having a distributed software layer negating the heterogeneity of the different devices located in the system. Finally, an API, security capabilities or semantic functionalities are not present in the system.

15. WAMPAC-Based Smart Grid Communications

Ashok *et al.* [58] stress how securitization of elements in a deployment is one of the most important features for a distributed, Cyber-Physical System, aiming to create a Wide-Area Monitoring, Protection and Control (WAMPAC) subsystem for this application domain. The authors have divided WAMPAC in a collection of subdomains: Wide-Area Monitoring Systems (WAMS), Wide-Area Control (WAC) and Wide-Area Protection Systems (WAP). SCADAs are used as a way to gather information from the environment they are present. The authors mention that this middleware solution is prone to have some challenges when it has to be deployed: WAMS, to begin with, has to be able to offer integrity, high availability and a level of confidentiality in utility data. WAMPAC schemes must also ensure that transferred messages are authenticated so as to isolate malicious information or commands. Moreover, the authors mention that a WAC making use of data collected from a Phasor Measurement Unit has been planned. The proposal can be further described as follows.

Service Availability: the subdomains that have been described by the authors are matching the levels that would be found in a middleware architecture. For instance, WAP requires large amounts of information collected from the deployed system, as it is required to make decisions based on that gathered data in order to counter any disturbance found. At the same time, WAMS is responsible for distributing information in an efficient, reliable way, making use of an underlying high-speed network infrastructure. WAC is also claimed to be a potential manner of providing applications specific to the power grid, such as inter-area oscillation damping, static control or secondary voltage control. It has to be noted that, as shown in Figure 21, WAMPAC is included as a part of a wider Smart Grid scenario used to solve security issues, instead of being a separated, portable middleware proposal.

Computational Capabilities: a WAMPAC controller makes use of data management solutions, networking and security, so it can be located as part of the infrastructure used for information exchange and communications and the infrastructure used for electricity generation and transfer, that is to say, the TSO/DSO domain.

Message Coupling: there are two different communication paradigms that are used in the proposal. The first of them is real-time, as it is mentioned that real-time communications are the most frequent ones that happen in the environment that has been put forward for the proposal. The second one is Publish/Subscribe, due to the fact that the proposal takes into account the suggestions made by the North American Synchro-Phasor Initiative (NASPI) about secure and synchronized data measurement infrastructure (NASPInet, [59]), where a Publish/Subscribe component is implemented.

Middleware Distribution: although the domain that is suggested for the proposal is clearly a distributed one, the degree of decentralization is less clear, as there is little information about how the devices with the proposal installed will be deployed. Taking into account the fact that there are several pieces of equipment that could have the solution installed while still keeping a certain hierarchy, the proposal can be regarded as a mostly decentralized one.

This proposal can be further described as:

$$SGM = SA(3) + CC(0||3) + MC(0||3) + MD(2) \quad (15)$$

Advantages of the Proposal: security is a strong point of this proposal, as the infrastructure and software components of the middleware solution have been built upon and around it. The usage of a game theory framework for securitization, as it is mentioned in the proposal, provides a unique perspective that is not frequently seen in middleware solutions for the Smart Grid.

Disadvantages of the Proposal: the solution does not provide information about all the other services that are not that related to securitization (for instance, semantic capabilities, how an API can be provided, etc.). The authors' proposal seems to be more oriented to offer a solution for secure data interchange that a true middleware proposal with a collection of services and hardware abstraction.

16. C-DAX Middleware

The authors of this proposal describe how secure middleware can be provided for the Smart Grid, according to the development works that have been carried out in the research project named Cyber-secure Data and Control Cloud for power grids (C-DAX, [60]). As it has been described in other proposals, solving security issues for data transactions is a major objective in this middleware solution, referring at them as Active Distribution Networks or ADNs. There are several pieces of hardware that could have the proposal

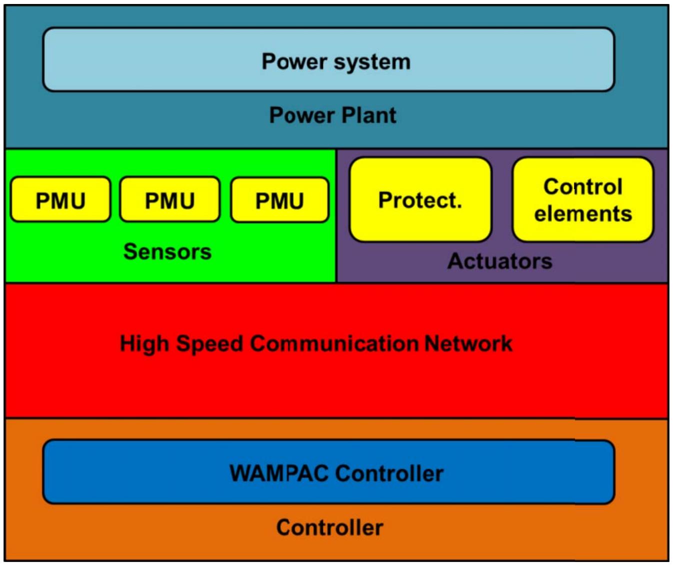

Fig. 22. WAMPAC communications, as depicted in [49].

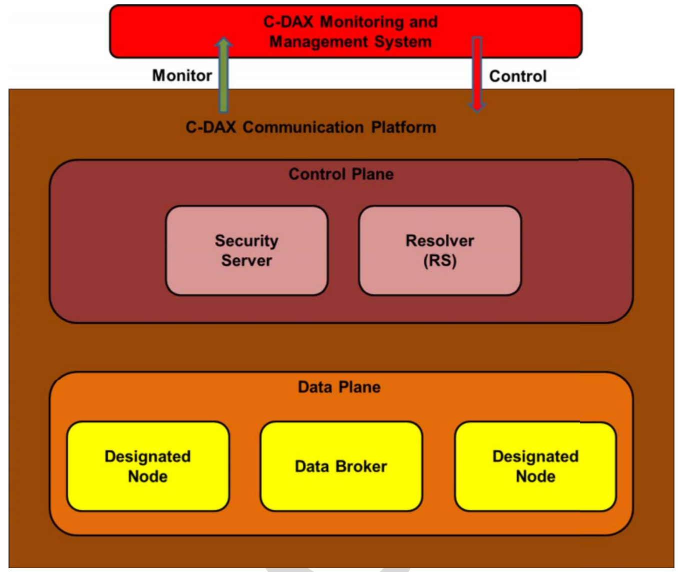

Fig. 23. C-DAX middleware proposal, as shown in [51].

installed for data heterogeneity abstraction, such as the already mentioned PMUs and other pieces of hardware like Phasor Data Concentrators (PDCs) and the ones related to Real-Time State Estimation (RTSE). RTSE-related applications have been conceived as appliances capable of collecting information from the PDCs and using it as input for a mathematical model used with the idea of estimating the actual condition of the Smart Grid. Additionally, PDCs are utilized for the reception of timestamped information that is also time-aligned and aggregated from different PMUs. As it is done with solutions based on DDS, topics have been defined with the purpose of separating different kinds of content. NASPInet is also used for PMU measurements as the protocol of choice.

Service Availability: the proposal has been considered as a Message-Oriented Middleware due to the fact that the middleware solution is focused on secure message interchange rather than providing mere hardware abstraction or a software architecture with several components included in it. There are two planes of information that have been created by the authors of the middleware solution: the *control plane* and the *data plane*. The control plane is used to contain the server with the security facilities included in the deployment and the resolver used to translate the information transfers that are done with security functionalities enabled. The data plane contains both Designated Nodes for communications, as well as a Data Broker for the management of information requests. The structure of the proposal and all its components are shown in Figure 23.

Computational Capabilities: the pieces of hardware used by the proposal fall into the conventional ones. It is also mentioned that tests used to check performance have been made with a data link of 100 Mbit/s. Since the main concern of the proposal is the transmission of information in a secure manner, it can be argued that the TSO/DSO infrastructure will be the one where the proposal will be most useful. Furthermore, hardware in power plants is also likely to have the proposal installed, as it would be capable of adding security to information that due to is nature must be encrypted for its data transmission.

Message Coupling: the middleware solution presented in this case describes three ways to interchange messages: *streaming communications* mode (utilized for subscribers to obtain information related to their topics of choice), *query communications* mode (used by subscribers to send explicit data queries) and *point-to-point* communications (where data are transferred without using Designated Nodes or Data Brokers). These three communication modes can also be explained as a Publish/Subscribe paradigm with application data published at one end of the communication and consumed by the subscribed at the other end of the communication, or a real-time paradigm where information is obtained from the Advanced Metering Infrastructure deployed in the Smart Grid.

Middleware Distribution: it has been considered that this is a mostly decentralized proposal because it is present in several appliances but at the same time there are pieces of hardware where data reception and delivery are also used, thus signaling a certain degree of hierarchy present in the system.

This proposal can be described with the following equation:

$$SGM = SA(2) + CC(2||3) + MC(0||3) + MD(2) \qquad (16)$$

Advantages of the Proposal: this middleware solution is bent on providing security for data interchanges, which is a major feature that it is often neglected by other intermediation software layers. Among the tests that have been carried out with this proposal, challenging scenarios involving Data Brokers have been one kind of them.

Disadvantages of the Proposal: the solution fails to deliver a significant number of services because it has been only considered for message interchange instead of as an architecture encasing software components resulting in services. As a consequence, some facilities that would have been welcome (for example, an API for interconnectivity with the application layer) are not present in this case.

17. Building As a Service (BaaS)

The main feature of the proposal presented by Martin *et al.* [61] is that Smart Grid-based capabilities are used in the very specific context of energy efficiency in buildings. The latter are conceived as entities used to retrieve services (hence the name of the proposal) that become interconnected at the data level by means of a middleware layer bent on optimizing energy consumption levels. Implementation works have been carried by means of the facilities offered by the Open Services Gateway initiative (OSGi, [62]), that are supposed to offer interoperability, transparency and openness. Interoperability among buildings is offered by using Building Information Models (BIMs), Data Warehouses (used to store data), legacy ICT facilities and Building Management Systems (BMSs). The proposal can be further explained with the following features.

Service Availability: the proposal has been regarded as a middleware architecture due to the fact that it has been divided in three different layers, as it is common among the studied middleware architectures. However, it has to be noted that among the different features conceived by the authors of the proposal, only the Communication Logic Layer is strictly part of the middleware, due to the fact that the other layers are either related to the application layer (containing services about models, modules and services kernel) or focused on data gathering. Indeed, there is a lower level called data layer that encases the Communication Logic Layer called Data layer; it is responsible for including information linked to the infrastructure utilized for the BaaS (it is described in the proposal how the ICT infrastructure weather and access control are the ones that have been thought of). At the same time, the Communication Logic Layer is further subdivided in two levels: *Core Communication sublayer* and *Data Access Object sublayer*. The first one is composed by the Domain Controllers or DCs and the Data Acquisition and Control Management (DACM). The Data Access Object sublayer contains components that somewhat mirror the ones that have been described for the other level: a DC Data Access Objects component has been included, along with a DACM Data Access Objects one for all the data related to DACM. The structure of the middleware architecture has been described in Figure 24.

Computational Capabilities: the services that have been included in the proposal are software components that have been implemented as bundles relying on OSGi technologies. It can be claimed that OSGi-based bundles usually take kilobytes of room (as reflected in ESB bundles using OSGi interfaces in [3] and [63]), so they should be able to be installed in almost every device present in the Smart Grid as long as there are minimum, reasonable hardware capabilities. Since the information that is gathered is done so from sensor readings, it can be argued that any intermediate hardware installed as part of the aggregator, DSO or TSO infrastructure should be able to contain the software packages.

Message Coupling: the middleware solution mentions in an explicit way that Client/Server communications have been used to transfer information, so it can be inferred that this is the paradigm that has been chosen for data transfers.

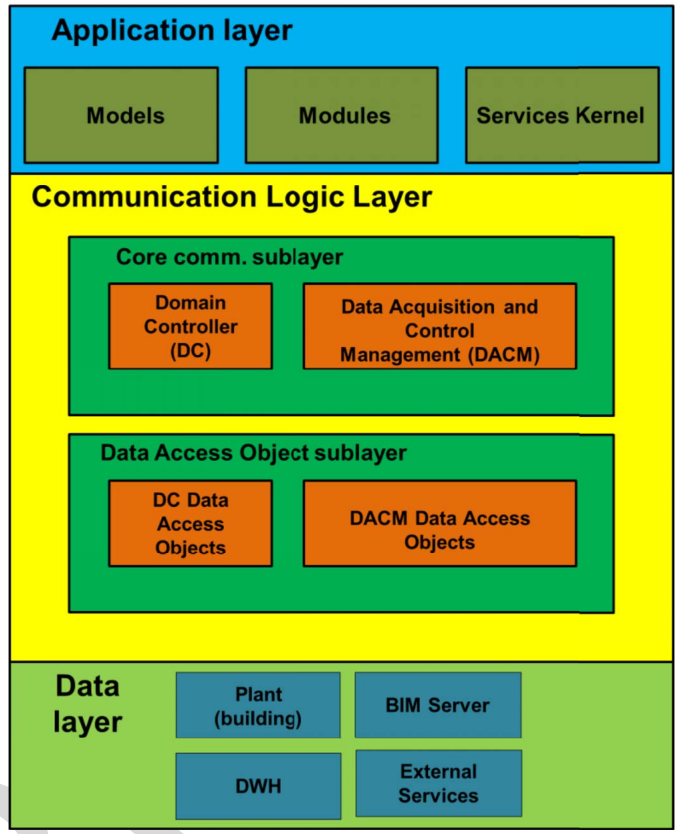

Fig. 24. Building as a Service proposal, as described in [52].

Middleware Distribution: this proposal has been regarded as a mostly decentralized one because the software components required for it to have a good performance are located in several buildings at once where the services are offered, yet there are still some elements that have a higher responsibility in the deployment that others (the Data Acquisition and Control Manager is one example of this fact).

When all this description is taken into account, the proposal can also be defined as:

$$SGM = SA(3) + CC(1||2) + MC(2) + MD(2) \quad (17)$$

Advantages of the Proposal: the middleware solution presented here has innovative concepts such as conceiving buildings as entities capable of providing services. In addition to that, an API has been built with the purpose of information interchange at the data level and as a way to interface levels among them. OSGi is use as a key technology of the proposal, which is consistent with the idea of providing open source technologies for the middleware as a way to optimize scalability for future developments that demand new services in the foreseeable future. Last but not least, there is a collection of other technologies that are easy to troubleshoot and develop for, given their degree of popularity and usefulness (Java Database connectivity in the data Warehouse software package, JavaScript Object Notation for the Building Information Model).

Disadvantages of the Proposal: the solution is lacking some services that are usually regarded as of major importance, like

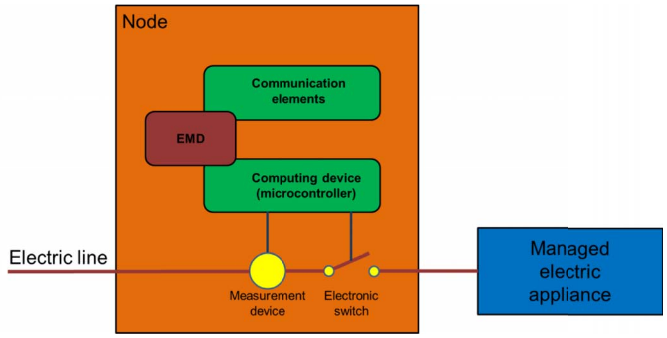

Fig. 25. Appearance of the device used for middleware-based management, as shown in [55].

semantic capabilities or how security is provided to the system. The domain that this proposal has been conceived for is also quite narrow, which may make challenging for the middleware solution to be deployed in other environments of similar characteristics.

18. Middleware-Based Management for the Smart Grid

The proposal that has been described by the authors deals with how a hardware platform can be used to integrate a series of elements used for management of electricity in the Smart Grid when combined with middleware [64]. In order to combine both hardware and middleware, a specific device for that purpose called Embedded Metering Device (EMD) has been manufactured by the authors of the proposal. Their purposes are: a) availability (segments of the network are able to still work despite failures), b) scalability, c) adaptability (since EMDs are conceived for devices that require no changes in their design) and d) hierarchical design for the overall performance of the proposal components. Other remarkable features of the proposal are related to the size of the hardware used for the middleware that has been encased in the proposal: low energy consumption, low cost, small dimensions, access flexibility and access transparency. The main, final objective of the middleware solution is becoming a generalist platform where power management services can be developed and installed. According to the authors' point of view, the device is used as part of Advanced Metering Infrastructure, so software components to be used as middleware are strongly linked to the device used for them. The appearance of the hardware and its components has been included in Figure 25. Its main characteristics are the following ones.

Service Availability: the main purpose of the proposal is device interconnectivity at the network (mostly because of the hardware that is provided) and data level (due to its software components). Because of this, the middleware solution has been considered as a hardware abstraction-based one, where the main bulk of the software is devoted to that functionality. Aside from that, there is no API provided as part of the middleware implementation efforts, so it is unclear whether it is expected from higher levels to access the middleware solution installed in the EMDs.

Computational Capabilities: the proposal is explicitly aimed to smart meters that are part of and Advanced Metering Infrastructure, so no other part of the Smart Grid is expected to carry the software components used for hardware abstraction, or abstract any other kind of hardware.

Message Coupling: the authors of the middleware solution claim that their prototypes work under CORBA [65], as well as the Internet Communications Engine (ICE), which offers a Remote Procedure Call (RPC) protocol iteration that offers standardized communications for the transport layer. Therefore, it has been considered that the proposal works mostly as a Client/Server paradigm.

Middleware Distribution: the proposal is linked to a single kind of device that is used for a specific purpose. Nevertheless, AMI are widespread in a Smart Grid-like environment, so it has been considered as a mostly decentralized proposal, due to the fact that it is still under some degree of control by elements that are outside middleware and work in a hierarchy.

Considering all the data provided previously, this proposal can be described as follows:

$$SGM = SA(0) + CC(0) + MC(2) + MD(2) \qquad (18)$$

Advantages of the Proposal: the authors have presented a device that is capable of using AMI as a way to connect middleware components among them with low capability devices. Cost or dimensions of the devices used has been taken into consideration too.

Disadvantages of the Proposal: the solution is solely focus on a specific, relatively limited goal in one specific kind of device, so its portability and scalability look quite challenging. The EMD device that is described makes use of CORBA as a way to transfer data and has been tailored for this solution, which makes hard for the device to use other standard or solution. Information about an API is not provided, and considering the functionalities expected from the proposal it may not be offered to the application layer. Lastly, services such as security, semantic capabilities or context awareness are not provided by the proposal, as its main objective is offering hardware abstraction rather than any other service.

19. OpenNode Smart Grid Architecture

Leménager *et al.* [66] have put forward their own solution for middleware in the Smart Grid based on the development works that have been carried out for the OpenNode project [67]. The proposal describes how the main concepts that are attempted to be achieved by the middleware proposal (modularity, extensibility, distribution of intelligence, open standards, cost effectiveness, common reference architecture) have been included in the design and implementation works. Basically, these were oriented to creating an open source proposal to be installed in the environment of Secondary Substation Nodes (SSNs), where middleware would be connecting them at the data level while running on this piece of equipment. Middleware, then, would be used to tackle stakeholder diversification and the flexibility needed for interoperability among the Smart Grid. The location of proposal as part of a larger system has been represented in Figure 26. The following features can be extracted from it.

Service Availability: the proposal that has been presented by the authors focuses on how hardware abstraction is provided

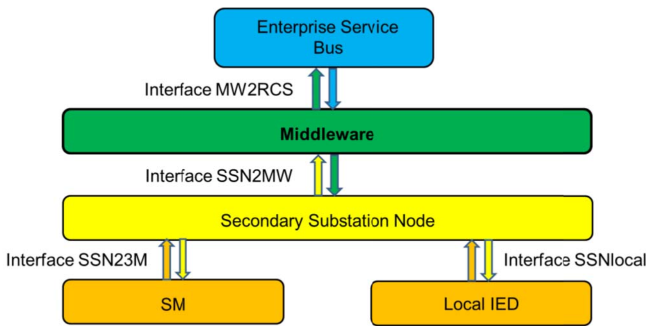

Fig. 26. OpenNode Smart Grid proposal, as described in [57].

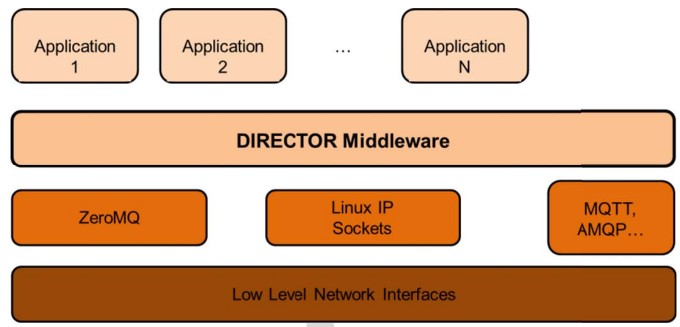

Fig. 27. DIRECTOR overall appearance, as shown in [59].

for the higher level components of the system that rely on it. Therefore, it can be regarded as a hardware abstraction middleware, due to the fact that the authors of the proposal have not conceived it as a way to have services that will be provided to entities outside middleware. Among the new components that have been developed for interaction with the elements of the system, the Secondary Substation Node is used for information interchanges with smart meters and local Intelligent Electronic Devices (IEDs) that will use middleware to interchange metering information, as well as grid automation data. The middleware layer will also transfer information to an ESB whenever data has to be transferred to other parts of the system.

Computational Capabilities: the authors of the middleware solution claim that the SSN prototypes have been built utilizing Personal Computers and embedded Linux CPUs. In addition to that, smart meters manufactured by five different vendors have also been used for testing activities. Therefore, it should be possible to have the proposal installed in end user's devices (Advanced Metering Infrastructure), aggregator facilities of the TSO/DSO domain.

Message Coupling: in spite of not having clear information about this characteristic in the proposal, it can be inferred that the system should be able to interchange information in a real-time way, due to its location in the overall system.

Middleware Distribution: according to the location of the proposal and the information given about it, this middleware solution will have to be considered as a fully decentralized proposal, due to the fact that is installed in several devices that are performing the same functionalities, without establishing a hierarchy or major and minor functionalities regarding its inner components.

Considering all the previously mentioned capabilities, the middleware solution can be described in a more accurate way by:

$$SGM = SA(0) + CC(0||1||2) + MC(3) + MD(3) \quad (19)$$

Advantages of the Proposal: the applicability of the solution that has been implemented is certain, as it has been integrated in a research project that must deliver results. Testing activities have been carried out in different environments showing that the developments that have been done are realistic and offer a feasible solution for interoperability at the data level.

Disadvantages of the Proposal: the solution is only oriented to interchange data from the Secondary Substation Node to the enterprise Service Bus used to interchange information with other parts of the system that has been deployed. Information about the overall proposal is lacking a description on the procedures about how messages are interchanged or how semantics is provided.

20. DIRECTOR

Wilcox *et al.* [68] describe what they refer to as a distributed communication transport manager for the Smart Grid. The authors of this middleware solution mention that DIRECTOR has been conceived as a tool to manage the requirements for applications communication in the context of the Smart Grid. The authors regard middleware here as a subcomponent of the DIRECTOR overall proposal, as it is placed between the applications and the socket Application Programming Interfaces right below the DIRECTOR middleware part itself. The messages present in the middleware domain encase work payload, the priory of the message and a list of destinations. Considering these facts and the matrix for middleware in the Smart Grid that was presented in Section II, the following assessment of the solution can be done.

Service Availability: hardware abstraction is the main functionality that the proposal is capable of providing. In addition to that, there is a certain degree of message orientation, evidenced by the fact that the socket configuration can be edited according to different levels of bandwidth efficiency. Therefore, the proposal has been regarded as an example of intermediation middleware. DIRECTOR has been designed with several different functionalities: a) an *application interface* (which has been conceived as an inter-process communication transport socket), b) a *network health* component (which is provided by monitoring data exchanges over an Ethernet bridge), c) a *custom transport layer* (generated after taking into account the inputs offered both by the application interface and the network health information), and d) a *custom socket* component (generated with the characteristics included during transport negotiation). Overall, the structure of the proposal has been described in Figure 27.

Computational Capabilities: it is expected that the proposal can be included by virtually any device present in the Smart Grid, as testing activities have been carried out in a Raspberry Pi. According to the authors and the specifications of the

Raspberry Pi model B [69] it has a 700 MHz ARM processor and 512 MB of Random Access Memory (RAM). Since a smart meter can be implemented out of a Raspberry Pi (as described in [70]), any kind of hardware from the ones defined previously can be used to contain the middleware layer of the proposal (end user devices, aggregator, TSO/DSO domains or the power plant).

Message Coupling: the authors of the proposal mention that it has been conceived for distributed and real-time embedded systems. In addition to that, it is also stated that a virtualized Demand Response Automation Server has been used as a way to simulate demand response environments, so it is likely that the proposal can also be used under a Client/Server paradigm.

Middleware Distribution: this solution has been considered to be a fully decentralized middleware proposal due to the fact that it works in a peer-to-peer manner, without any component that is adding any major prominence in a hierarchy. It has to be noted, though, that little information is offered about how data are interchanged in this solution in a way that further information can be hinted about this transaction process.

Considering the previous features that have been described in the proposal, the middleware solution can be described as follows:

$$SGM = SA(1) + CC(0||1||2||3) + MC(2||3) + MD(3) \tag{20}$$

Advantages of the Proposal: the authors of DIRECTOR have made clear the importance of having hardware devices to test the proposal in realistic scenarios. Furthermore, the middleware proposal has used a data model in order to check how applications would work. Last but not least, the concept of middleware is clearly stated by the authors of the solution, who are placing it in an explicit way between the application level and the sockets utilized by transport layer communications.

Disadvantages of the Proposal: there is a collection of major services (those related to security, semantics and context awareness) that are not mentioned to be present in the proposal. Overall, there is little information regarding any service that is not going beyond mere interoperability among pieces of equipment. It is also mentioned how data are transferred via transport layer and all the layers that are located below, but information transmission in higher levels (specifically, to the application one) is more scarce, and no API is provided as a way to make sure of how middleware facilities can be accessed from the application layer. Finally, information about message coupling is missing and makes hard to tell how data are transferred among several parties using the proposal as middleware solution.

21. DDS Interoperability for the Smart Grid

This is another proposal that makes use of DDS in order to create a middleware framework where the authors described how it should be implemented [71]. Data Distribution Service has been used in addition to standard interfaces and data structures with the purpose of having a scalable Smart Grid infrastructure used as a test bench to prove the feasibility of the solution that has been put forward. Among the functionalities that the proposal is claimed to provide, experimentation, algorithm testing or data gathering are cited as several of them. Interoperability with other solutions is offered by means of Real Time Publish Subscribe protocol (RTPS) at the lower level of middleware. At the same time, an API has been developed for higher levels to guarantee access to the middleware services. The proposal can be described with the following elements.

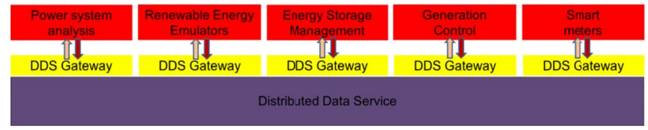

Fig. 28. DDS interoperability framework, as shown in [62].

Service Availability: this proposal can be regarded as a Message-Oriented Middleware, due to the facts that a) the main objective of the middleware solution is offering connectivity between devices present in the testbed and the applications that are offered to the end users instead of encasing several devices as functionalities to be offered to the surrounding elements of the system, b) the proposal is put forward by its authors as a manner to have a certain gateway between higher and lower levels and c) an API is offered to the highest level of the proposal so that middleware facilities can be accessed. The behaviour of the proposal and how it interacts with other elements have been described in Figure 28.

Computational Capabilities: it is expected from the devices that are going to mount this proposal that they will be able to run it without any problem, so at least they should have a significant amount of capabilities. Considering this and where the proposal could be most useful, the aggregator and the TSO/DSO infrastructures are the most likely to use the proposal to their advantage.

Message Coupling: it is explicitly mentioned both by the proposal and the underlying standard used that Publish/Subscribe is the way that is been chosen to deal with message coupling. Real-time data is also mentioned to play a role in the proposal, as it is a kind of transmission information that can be used by the RTPS layer of the middleware solution.

Middleware Distribution: even though there is not much information about how distributed the proposal is expected to be, it has been mentioned by the authors of the proposal that makes use of a DDS layer to send information to a collection of Smart Grid-related devices (generation control, smart meters, RESs). In order to take that kind of actions, it can be inferred that requests will have to be done from a single entity to several others. Thus, it can be argued that this is a mostly centralized proposal.

The middleware solution can also be described as:

$$SGM = SA(2) + CC(1||2) + MC(0||3) + MD(1) \tag{21}$$

Advantages of the Proposal: as previously stated, the pros and cons of this solution are strongly linked to the fact that DDS is being used for the design and implementation of the solution. Therefore, DDS is capable of providing a framework where the most typical functionalities expected of middleware can be provided. What is more, actual tests on real deployments have been made, so the proposed solution is known to work in a realistic manner in an environment like this. Lastly, an Application Programming Interface has been provided as a way to access the services provided at the middleware level.

Disadvantages of the Proposal: as it happened with the other DDS-based proposal, the usability of the proposal is strongly linked to DDS, so even though it provides a very accurate framework provided by the standard, all the facilities that are going to be used will have to be implemented from scratch. Therefore, any service that wants to be added will have to be implemented (semantic capabilities, context awareness, security) if the proposal is ported to another system.

22. Distributed Middleware Architecture for Attack-Resilient Communications in Smart Grids

Wu *et al.* [72] put forward their own ideas regarding how a middleware architecture could be created for more reliable communications in the application domain of this manuscript. In their contribution, it is acknowledged how middleware can be used in conjunction with DERs as a way to manage the data that are generated in scattered locations. Communications present in the system are regarded by the authors as being located in three different layers: the power-system application layer (which considers the industrial protocol IEC 61850 as the cornerstone for the power-system application layer), the control layer (where the middleware the proposal is dealing with would be located) and the network infrastructure layer (consisting of all the network-related facilities present in the system: network interface layer, transport layer according to the TCP/IP architecture and the Internet layer). According to the description done by the authors of the proposal, the following rules can be inferred.

Service Availability: Although the authors claim that they have developed a middleware architecture, the authors of this manuscript have classified this solution as an intermediation middleware, due to the fact that middleware is used to interoperate among the application layer and the underlying network and hardware components. Plus, little is mentioned about the software services that are expected to be provided by middleware. Among other components, this middleware proposal also includes QoS parameters in accordance to the criteria defined by the IEC 61850 standard used for the power system part of the proposal. The role that the middleware plays in the proposal has been depicted in Figure 29.

Computational Capabilities: it is never mentioned what devices would be expected to have the middleware solution installed, but judging from the management capabilities that they have been given they are not likely to be present in the AMI or the aggregator parts of the system. Besides, it is mentioned in the proposal that it is making use of the IEC 61850 protocol, so it is expected that middleware could be used in the TSO or DSO application domain.

Message Coupling: the proposal mentions having a distributed, real-time middleware architecture as one of the objectives of the middleware proposal, so the kind of message coupling that is used in this case can be inferred from that statement. No other kinds of message coupling paradigms are described in the middleware solution.

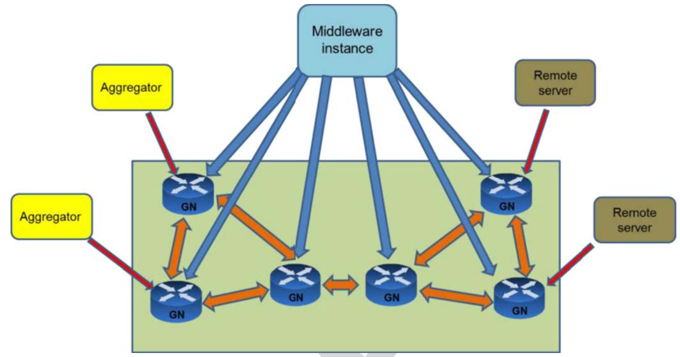

Fig. 29. V. Distributed Middleware Architecture for Attack-Resilient Communications, as described in [63].

Middleware Distribution: even though the middleware is best fitted for a distributed environment, it has been represented as an entity that is centralized in a single component in the representation of the proposal, so it has been regarded as a mostly centralized one.

The middleware proposal that has been presented here can also be depicted as follows:

$$SGM = SA(1) + CC(2) + MC(3) + MD(1) \tag{22}$$

Advantages of the Proposal: as previously stated, the proposal acknowledges the importance of security and preventing attacks. Furthermore, testing activities have been done and a significant amount of information about them has been added to the proposal. Also, the proposal makes a strong effort in enhancing the capabilities of Quality of Service and Experience.

Disadvantages of the Proposal there is very little information about the middleware itself, as the main ideas that are learnt from the proposal is that it is distributed and attack-resilient. The focus of the research that has been described in this proposal is mostly about preventing attacks that may jeopardize the security of the communications that have to be established in the Smart Grid, rather than showing what software services can be offered to the applications or the devices aside from security (context awareness, device registration, semantic capabilities, etc.).

23. Real-Time Middleware Platform Based on ETSI M2M Middleware

Predojev *et al.* [73] aim to create a middleware platform that can be used as a way to add Machine-to-Machine (M2M) technology to middleware, while at the same time using the facilities that are offered by the ETSI [56] architecture developed for M2M communications. The authors mention how three main communication requirements have been identified for the Smart Grid: Quality of Service (data latency and its requirements for protection, control, monitoring, reporting, billing and post-incidental analysis), flexibility (easiness to handle information updates, functionalities for filtering information, etc.) and security (so as to deny access to unauthorized

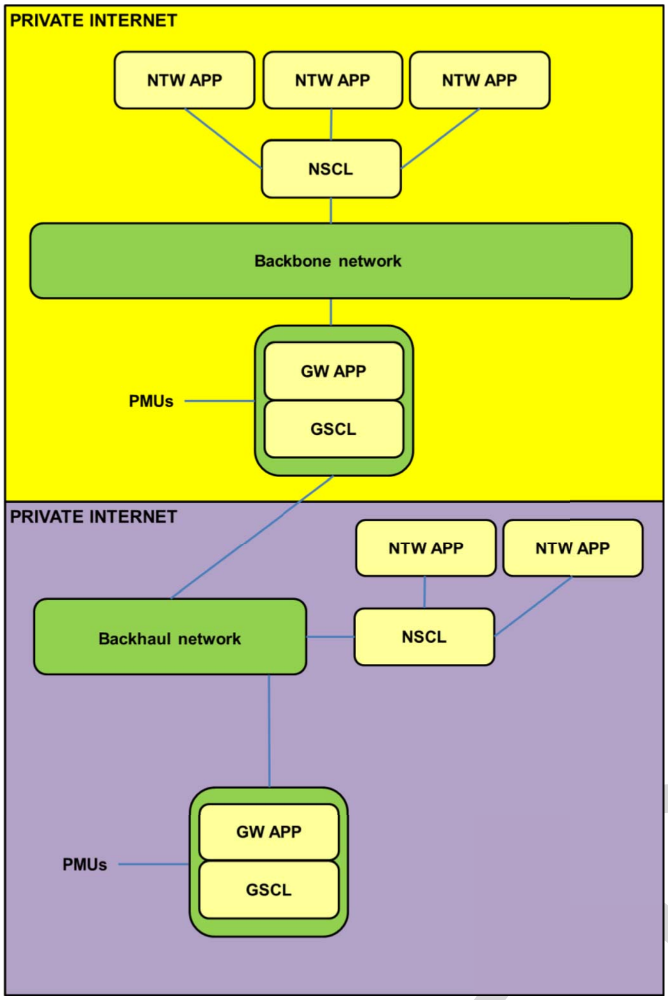

Fig. 30. High level mapping of ETSI M2M components, as described in [64].

parties as well as providing data integrity and confidentiality). In addition to that, the authors stress the importance of Web services as a way to offer access to the facilities middleware can provide. The authors also claim that the advantages that are offered by their proposal are: a) halving network latency, b) reducing network overhead and c) doing away with acknowledgement messages sent throughout the communication process. The proposal has been described according to the following ideas.

Service Availability: this proposal has several modules that have been called *Service Capability Layers* (xSCLs). There are three different kinds of them; network, device and gateway (thus having NCSL, DSCL and GSCL). It is claimed by the authors that each of the xSCLs withholds the complexity of the underlying network, too. Finally, there are two layers that have been used to build this proposal: one deals with transmission and contains all the elements associated to the backbone network, whereas the other one is based on distribution and encases all the elements related to the backhaul network. Therefore, it has been considered by the authors of this manuscript that this is a middleware architecture. A high level representation of the proposal that has been described by the authors can be seen in Figure 30.

Computational Capabilities: it is expected that the middleware can be accessed by applications used for the benefit of the end user. In addition to that, the computational capabilities of the software employed as an inspiration (CORBA) are not that demanding, so it could be said that the proposal will be installed in the aggregator facilities, or even in the TSO and DSO domains, due to the fact that there are several software elements that are providing management and support, rather than information from end users or the electricity produced at a power plant.

Message Coupling: the middleware solution mentions that it is aimed at providing a real-time middleware platform, so that communication paradigm is provided with no question. Additionally, it is also mentioned how clients can access services via HTTP requests, so it can be inferred that it can also be used as a Client/Server system.

Middleware Distribution: despite having little information about how the proposal would be distributed in an actual Smart Grid, it can be argued that it will be present in several elements of a deployment rather than in a single one. Also, considering the existence of certain hierarchy present in the software components that have been defined by the middleware, the solution has been considered a mostly decentralized one.

Taking into account the previously inferred characteristics, the middleware solution can be described as follows:

$$SGM = SA(3) + CC(1||2) + MC(2||3) + MD(2) \tag{23}$$

Advantages of the Proposal: this proposal has been tested under actual scenarios where information about its performance has been collected. The existence of a way to access the facilities from the middleware solution via REST makes service availability more convenient and feasible that in other proposals lacking interfaces that offer information to the end user.

Disadvantages of the Proposal: there are very few data about how services behave in the described solution. Also, there is plenty of information regarding how services can be accessed, but information about specific mechanisms to offer major functionalities as context awareness, security or semantic capabilities are missing or seldom mentioned in the middleware solution.

24. Apache Spark As Distributed Middleware for Power System Analysis

The proposal that has been developed by Šuti and Varga [74] makes use of the services provided by Apache Spark as a big data engine devoted to functionalities related to data processing. This solution is primarily aimed to power flow analysis in a distributed environment, and has been included as an intermediate layer between the facilities related to the network level and the business logic that makes use of the output provided by the iteration of Apache Spark used during testing activities. Considering the description that has been made by the authors of the proposal, the following features can be inferred from it.

Service Availability: this proposal is solely focused on providing functionalities related to a specific feature, so aside

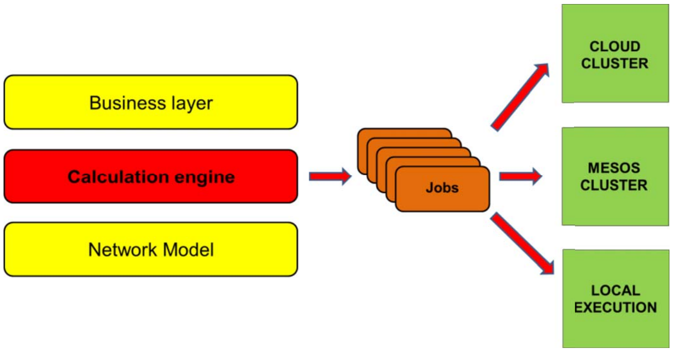

Fig. 31. Apache Spark interaction components, as described in [65].

from power flow it is not expected to be used for anything else. Thus, it is has been considered a hardware abstraction architecture. Figure 31 shows how it interacts with the above and below layers, along with how jobs are used for each of the clusters that are involved in the proposal.

Computational Capabilities: the only thing that may suppose a challenge for a machine is the installation and regular performance of Apache Spark in a machine. Considering that it is a tool that can be run in any PC or laptop with standard capabilities it can be argued that, while it would be a challenge running Apache Spark in a low capability device such as the ones found as Advanced Metering Infrastructure, it could be run with next to no issues in any other kind of hardware comprehended within the area of knowledge of the Smart Grid, such as the Aggregator, TSO/DSO or the very power plant where electricity is produced.

Message Coupling: the middleware proposal that is described here does not specify a messaging system that can be used so that data will be transmitted. Nevertheless, it can be assumed that Client/Server communications should be possible, considering that requests can be done to the layer where Apache Spark has been deployed.

Middleware Distribution: despite the lack of information about this feature in the proposal, it is stated how information can be interchanged between the machine where Apache Spark is deployed and several clusters with several computers each. Thus, it can be said that this is a mostly centralized proposal.

If all these characteristics are considered, this architecture can be described with the following equation:

$$SGM = SA(0) + CC(1||2||3) + MC(2) + MD(1) \qquad (24)$$

Advantages of the Proposal: this proposal can run easily in different kinds of devices, due to the fact that its most important requirement is the capability of a piece of hardware to run Apache Spark. Therefore, it makes the proposal very flexible and easily portable, as it relies on software tools that are widely known and used.

Disadvantages of the Proposal: this proposal is used just as a way to obtain information for power flow, rather than encasing a collection of services able to provide a more general use. Major facilities that should be included like semantics, registration procedures or context awareness are absent from the proposal. Additionally, there is too little information regarding how the proposal is distributed among a set of computers or the kind of messaging system that is used.

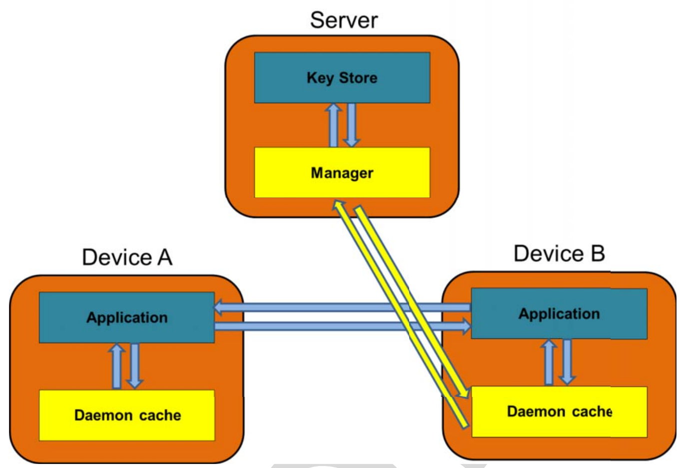

Fig. 32. Structure of the secure proposal, as described in [66].

25. Security of Communications on a High Availability Mesh Network

The authors of this proposal cite mesh networks as a way to quickly reconfigure a network with devices from the Smart Grid [75]. However, since they are aware of the security risks associated to this kind of network, they make use of a middleware solution called SECOM deemed capable of improving the whole system reliability, as it is based on a key server charged with storing information about the authorized devices present in a network.

Service Availability: this proposal has been regarded as a hardware abstraction middleware, as it is considered to be located as part of the network infrastructure that makes possible the mesh network. Figure 32 shows the kind of structure that has been created for data transmissions.

Computational Capabilities: since the proposal has been located in several pieces of equipment used for data transmission and are receiving requests from applications (likely to be used by end users) it can be claimed that the proposal could be deployed in the aggregator or the TSO/DSO domains.

Message Coupling: the most prominent way of interchanging data middleware is performing requests against the servers, so the proposal has been considered as following the client/server paradigm.

Middleware Distribution: the proposal is expected to work in mesh networks while still retaining some degree of hierarchy (as it can be inferred from the fact that there are servers attending petitions made from devices), so it has been considered to be a mostly decentralized one.

Taking into account the previous criteria that have been formulated, the following equation can be obtained:

$$SGM = SA(0) + CC(1||2) + MC(2) + MD(2) \qquad (25)$$

Advantages of the Proposal: this proposal takes into account the security threads that might be present in a system like the

Smart Grid. There are several tests that have been carried out in order to ensure that the proposed solution was matching the expectations the authors of the solution had on it.

Disadvantages of the Proposal: although security is heavily stressed, there is little information about any other kind of services that are present in it. Capabilities as context awareness or semantics are not present in the proposal. Mechanisms like registration or how services like Demand Response or Demand Side Management are offered is not explained either. Finally, the proposal is more focused on what can be done at the network layer than at the middleware one.

26. Open System for Energy Services (OS4ES)

The middleware proposal that is described in this case has been created under the framework of a research project that has been called OS4ES (Open System for Energy Services) [76]. Here, it is described how the objectives of the project range from delivering a reference architecture of an open system based on energy services, along with its implementation works, to standardize it according to the facilities provided such as an API for energy management applications or an interface for distributed system registry. The works done under this project make possible the existence of a software system between several entities related to end users (aggregator, DSOs, retailers, etc.) and hardware devices gathered with each other as Virtual Power Plants (VPPs) that makes use of a semantic middleware that has been embedded between the application and the communication layer. This middleware can be further described by following the same pattern used in the previous proposals.

Service Availability: it is mentioned in the documentation of the project that there are four basic blocks of capabilities: a) registry of DER systems, system functions and services used for information retrieval, b) functionalities of the system, c) information conversion and d) control layer. Although it is not explicitly described in the proposal the location of these functionalities (the OS4ES system developed involves communications, middleware and applications), it can be argued that the intention of the project is having the implementation done as something roughly equivalent to an intermediation middleware, as it is used as an intermediation element between the communication layer and the application one. A perspective of the location of the middleware in the project has been included in Figure 33.

Computational Capabilities: even though there is little said in the documentation that has been elaborated by the participants of the project, the middleware can be expected to be installed in any machine that is not present in the front end of the system. In addition to that, it is mentioned as a component out of the Virtual Power Plants that are represented in the documentation. Thus, it can be placed either as in the aggregator domain or the TSO/DSO domain.

Message Coupling: while there is a mechanism for publishing and advertising DERs, it is explicitly mentioned in the proposal that a) communications are established in the middleware on a real-time basis and b) the conversion layer that has been added for information formatting makes use of Client/Server functionalities, so it has been regarded as a client/server, real-time communications proposal.

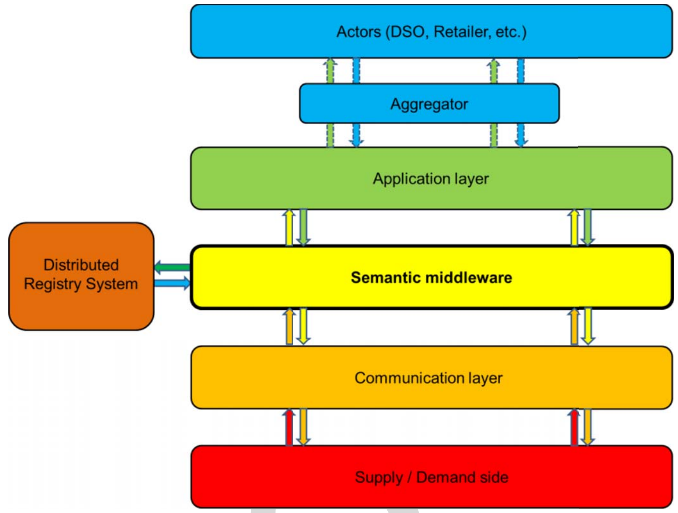

Fig. 33. Location of the semantic middleware, as described in [67].

Middleware Distribution: the proposal described as in [77] mentions how it is possible that the system can be deployed in a fully centralized fashion (with all the components running in a single device), a fully decentralized one (where there are several devices running the most prominent components) and a mixed one that is mostly decentralized but there are still some centralized control elements. Consequently, it can be regarded (depending on the particular deployment used) as a fully centralized, mostly decentralized or fully decentralized middleware architecture.

Taking into account the previous classification obtained, it can be said that the architecture can also be described with the following equation:

$$SGM = SA(1) + CC(1||2) + MC(2||3) + MD(0||2||3) \tag{26}$$

Advantages of the Proposal: the semantic middleware that has been described in this proposal is fully embedded in the most suitable location for middleware. Also, the functionalities that are implicitly performed by the proposal are matching what is expected from middleware (hardware abstraction, intermediation). Additionally, the middleware has been included as part of a bigger proposal in a research project, so it is a truly functional semantic middleware.

Disadvantages of the Proposal: despite the ambition of the proposal that is presented, there are several aspects that do not completely match the functionalities that can be found in a middleware proposal: for example, it is said that the middleware needs IP address to deal with communications, whereas it would be desirable that it was isolated from the network layer functionalities or features. Furthermore, even though requirements have been listed with precision, there is not a comparable list of the services that are available in it as developed software components. Lastly, the explanation of the functionalities that are described in the project tend to overlap and be mixed with the ones found as part of the middleware layer.

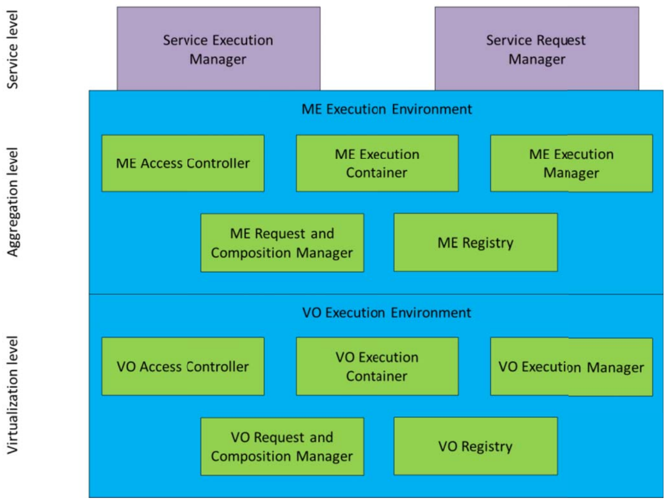

Fig. 34. Architecture components, as described in [69].

27. Cloud-Based and RESTful Internet of Things Platform to Foster Smart Grid Technologies

The authors of this proposal put forward a platform that, considering that makes use of REpresentational State Transfer (REST) interfaces and is located in the cloud, can be deemed as a middleware proposal [78]. Their prime objective is creating a framework able to guarantee interoperability, scalability, reliability and reusability to the Smart Grid, according to the targets mentioned by the Smart Grid's Strategic Research Agenda of the European Union and the National Institute of Standards and Technology (NIST). In order to accomplish these objectives, a solution has been implemented that attempts to encapsulate each of them in the different software components that have been developed. Tests of the implemented solution are also provided as part of the activities that has been carried out related to it.

Service Availability: the proposal described by the authors falls within the definition of a middleware architecture, as there are three different levels that comprise several components. These are: a *virtualization level* (made with Virtual Objects or VOs and also used to interface components of the architecture with a need for interaction in the real world), an *aggregation level* (made up by several Micro Engines or MEs) and a *service level* (which shapes application requirements into services that are provided by the MEs). The VOs make possible the virtualization of devices that are present outside the system, which are referred to as Real World Objects (RWOs), whereas the MEs comprise several VOs with the purpose of obtaining specific functionalities. Lastly, the service layer has a Service Request Manager that delivers requests to the aggregation level, and a Service Execution Manager that supervises service executions. The overall appearance of the architecture has been described in Figure 34.

Computational Capabilities: in the experimental tests that have been carried out there are several data sets that have been included in two Raspberry Pi devices that feed the proposal with data. Consequently, it can be inferred that it could be placed in any part of the system that is not part of the end user infrastructure: the aggregator, the DSO/TSO environment or the power plant could have the middleware solution installed.

Message Coupling: in spite of not having information about this feature in the proposal, it is said that it can process information provided in real time such as weather, so it will be considered that real time data can be processed.

Middleware Distribution: both in the description of the proposal and in the tests that have been done is mentioned that the proposal relies on a cloud-based deployment, so if both this fact and the existence of a hierarchy are taken into account it can be said that is a mostly decentralized architecture.

Hence, the middleware solution can be described with the following equation:

$$SGM = SA(3) + CC(1||2||3) + MC(3) + MD(2) \tag{27}$$

Advantages of the Proposal: this proposal is aimed at dealing with the major features that have to be offered by middleware, such as solving the issues that present having different and proprietary technologies cooperating with each other in a distributed system as the Smart Grid. Furthermore, there are several capabilities that have been included in the proposal that are more sophisticated than in others where no software components are embedded in the middleware.

Disadvantages of the Proposal: despite including several software components, the proposal does not make use of any kind of semantic capabilities, context awareness or services that can provide an added value to the proposal itself. Alas, although tests in a simulated environment are welcome, it would have been better to have deeper tests with a plethora of devices that matched the working scenario in a more realistic manner.

28. Software Defined Based Smart Grid Architecture

The authors of the middleware solution that is described in this paper describe a solution that involves an architecture making use of the Software Defined System paradigm [79], as they claim it can be used to decrease control overhead and manage operations in complex environments in a more efficient way. The authors attempt to extend to the Smart Grid the research and implementation works that have been done in Software Defined Networks or Software Defined IoT. Quality of Service is another major concern for the authors of the proposal: one of the two use cases that have been created by them takes into account QoS classes that become categorized and prioritized by means of a network services list along with minimum and maximum data rates.

Service Availability: the middleware solution described in this piece of work has been regarded as an architecture, as it is divided in three layers and each of them has a specific set of software components: the *asset layer* is the lowermost one, and involves the devices that have been deployed in the system gathered as power resources, storage resources and consumption resources. Secondly, the *sensing layer* contains the network infrastructure required to monitor and track the status of the underlying hardware systems. Lastly, the *control layer* encases the APIs required to control and manage the transactions that are carried out in the system; they have

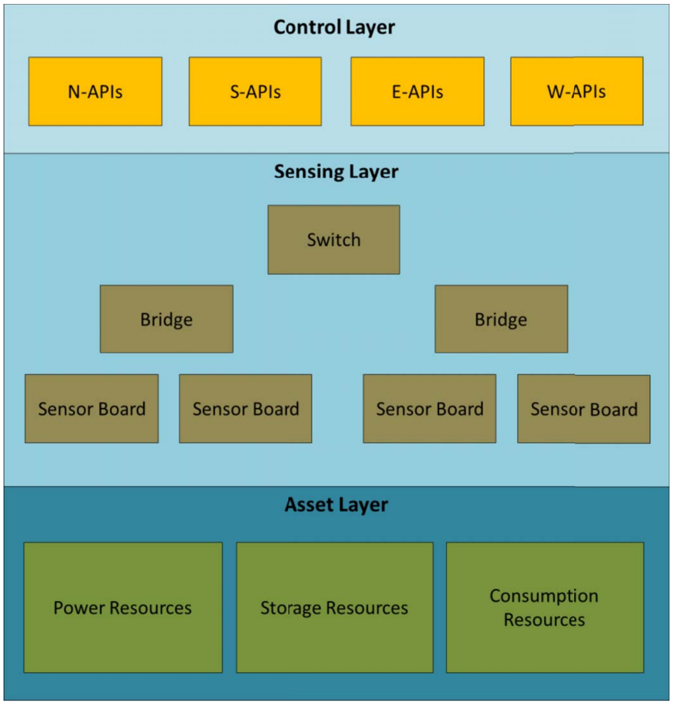

Fig. 35. Framework of the proposal, as described in [70].

been named after cardinal points (North, South, East and West APIs). It has to be noted, though, that the authors do not refer to their work as a middleware proposal, but use middleware as a way to execute changes in a programmable manner and abstracting control processes to it. The structure of the proposal as described by its authors has been displayed in Figure 35.

Computational Capabilities: the proposal includes several elements that are typically found in a distributed system related to the Smart Grid, such as devices related to power usage on the one hand, and network infrastructure used to transfer information on the other. Considering these facts, the system can be deployed in any part of the Smart Grid that does not involve usability for the end user (as the APIs that are provided should be used for the applications that will be built as an external part of the system), such as in the aggregator, DSO/TSO or the power plant domains

Message Coupling: the ability to establish Publish/Subscribe communications as something desirable is explicitly cited by the authors of the proposal, and it is indeed explicitly mentioned as something provided by it, as there is a Publish/Subscribe Unit offering those capabilities. In addition to that, the proposal itself features heavily real time data transmission, so it has been regarded as a solution that makes use of real-time solutions in terms of message coupling.

Middleware Distribution: the proposal itself is cited to make use of several elements of a distributed network that keep a hierarchy among them (switches, bridges, sensor boards), so it has been regarded as a mostly decentralized proposal.

Taking into account all the features that have been described previously, this proposal can also be described with the following equation:

$$SGM = SA(3) + CC(1||2||3) + MC(0||3) + MD(2) \quad (28)$$

Advantages of the Proposal: this proposal attempts to create a holistic architecture that involves all the components based on hardware and software that can be found in the Smart Grid. A series of APIs are offer as a way to provide connectivity between the architecture and the system itself, so having applications that make use of the system should be an easy task to deal with.

Disadvantages of the Proposal: the proposal covers far more than what is expected from the middleware and includes hardware elements that should not be part of a middleware solution. Clearly, the authors were aiming more at creating a full stack architecture that covers every aspect imaginable for interoperability in the Smart Grid, rather than having just a middleware solution for hardware interoperability.

29. Distributed Software Infrastructure for General Purpose Services in Smart Grid

This proposal aims to provide an event-driven, service-oriented middleware for hardware interoperability among the elements present in the Smart Grid [80], taking into account four different objectives: a) offering feasible integration for heterogeneous technologies, b) enabling the access from multiple actors to control technologies as well as relevant data, c) enabling interoperability with third party software and d) making hardware interoperability possible throughout the system. In order to do so, the authors of this proposal have created a middleware solution with several components called *managers*, which follow a Service Oriented Architecture (SOA) approach. This proposal relies on the ideas and implementation works done as part of the Internet of Things and ubiquitous computing.

Service Availability: the solution that is described in this proposal falls within the category of a middleware architecture, as it follows the regular pattern of such a development. There are three layers on this proposal: the *application layer* (used by the proposal to interact with the applications that lie immediately above it), the *services layer* (containing several software components used for interoperability purposes) and the *integration proxy layer* (used to abstract the heterogeneity of the deployed hardware). Most of the services are contained in the services layer, as it has five different managers (used for networking, events, trust, security and discovery services) and two frameworks (one used for rules and another one for semantic capabilities). The main components of the middleware have been depicted in Figure 36.

Computational Capabilities: according to the tests done and described by the authors of the proposal, it is expected that it can be installed in any network of devices that can operate following regular network bandwidth and equipment, so as long as this middleware proposal remains as part of the end user devices, aggregator or the TSO/DSO domains it can be deployed with no issues at all. The distribution network that is used under the middleware deployment reflects that aspect as well.

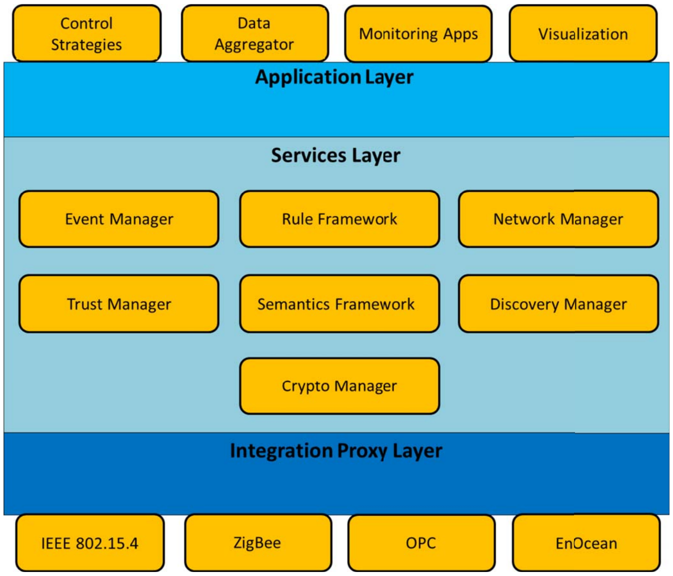

Fig. 36. Main components of the proposal, as described in [71].

Message Coupling: both the usage of a publish/subscribe paradigm are real-time communications are explicitly mentioned in the proposal, so they have been included in the equation used to describe the proposal.

Middleware Distribution: the proposal is expected to follow a pattern resembling other middleware architectures. Consequently, it has been regarded as a fully decentralized architecture that is deployed in several hardware components but still with a similar degree of intelligence in each of them.

Taking into account all these features, the proposal can be described with the following equation:

$$SGM = SA(3) + CC(1||2||3) + MC(0||3) + MD(3) \tag{29}$$

Advantages of the Proposal: this proposal offers a collection of services that have some of the most prominent services that can be developed (security, semantic capabilities), as well as facilities that abstract hardware heterogeneity and offer access to the devices and the applications to the whole system.

Disadvantages of the Proposal: there are some elements that have been included in the proposal that overlap with the functionalities that other levels usually have, such as the existence of an application layer within the middleware solution itself.

30. Distributed Middleware Architecture for Attack-Resilient Communications

The authors of this proposal mention how the integration of Renewable Energy Sources brings the issue of integrating scattered DERs into the power grid [72]. They aim at making that possible by means of using the IEC 61850 protocol as a way to develop a middleware solution that will be used for those purposes. It can be inferred from the proposal that one of its purposes is that even though the IEC 61850 protocol was first conceived for communications among substations, it can be extended to other fields related to interoperability regarding information transfers.

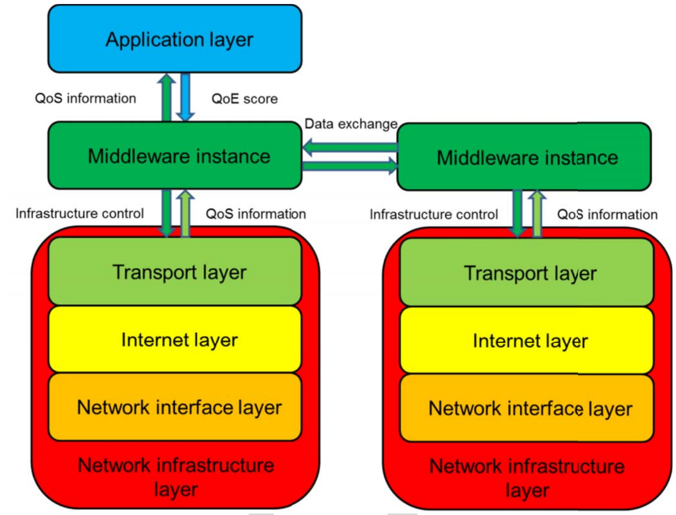

Fig. 37. Middleware interactions, as described in [72].

Service Availability: this proposal is oriented to transfer information from one element of a networked deployment to another one, while at the same time being located between the application and the transport layers, so it can be regarded as a Message-Oriented Middleware. Tests have been done by means of the NS3 emulator and MATLAB in order to assess the performance of the proposal, which improves the data flow when compared to a deployment when this middleware solution is not installed. As it happens with other proposals, QoS parameters are taken into account, as well as Quality of Experience (QoE) information obtained from the end users. Figure 37 shows the location of the middleware among all the other elements that would be included in a deployment.

Computational Capabilities: considering that the middleware proposal is located in an entity capable of sending bidirectional information between the aggregator and the remote servers, it can be claimed that it would be installed in the DSO and TSO domains.

Message Coupling: communications were explicitly described as real in the tests that were carried out, so the solution has been considered as using real time transfers in terms of message coupling.

Middleware Distribution: it is mentioned that the messages are transferred through a networks of devices without having any prominent element in each of the devices where they are installed, so it has been regarded as a fully decentralized middleware.

Thus, this middleware solution can be described as follows:

$$SGM = SA(2) + CC(2) + MC(3) + MD(3) \tag{30}$$

Advantages of the Proposal: this proposal makes use of a widespread standard that has been accepted and worked on in industry for quite a while. The tests made show that the solution has been successful in improving the existing state of the art for data transfer and interoperability in a simulated environment.

Disadvantages of the Proposal: there are several services that could also been included, such as context awareness or semantic capabilities that are often present in middleware architectures.

31. Tailoring DDS to Smart Grids for Improved Communication and Control

This is another solution that makes use of DDS as a way to have interoperability and interconnectivity at the data level among several devices of the Smart Grid. The authors of this proposal describe how DDS can be used to tailor a layer for communication and control in a Smart Grid [81]. A sit happened with other proposals, the importance of Quality of Service parameters, as well as the usage of a publish/subscribe paradigm are of major importance, as they are require to have a good grasp on the performance of DDS.

Service Availability: DDS tends to be used in a context of middleware architectures, as it is of major importance for software services implementation and deployment. However, rather than providing a specific set of services and a design, general information and guidelines are provided in this proposal.

Computational Capabilities: DDS can be deployed in any kind of equipment that is as powerful as a Personal Computer or a laptop, so having it running in any place of the Smart Grid should not be a problem. QoS parameters used to interchange communications are of major importance, as latency and reliability are explicitly mentioned by the authors.

Message Coupling: DDS makes use of a publish/subscribe paradigm wherever it is installed, so it can be expected to be run like that. On the other hand, device discovery is done via the real time protocol that has been described before (RTPS), so communications in real time are contemplated as well.

Middleware Distribution: DDS is usually configured as a mostly decentralized architecture in middleware solutions. However, the work that has been shown by the authors in this case does not provide actual information about deployments done in pieces of equipment.

Advantages of the Proposal: this piece of work offers a set of guidelines and procedures on how to port DDS to the environment of the Smart Grid, which has already been proven as a desirable standard to use under distributed, Cyber-Physical Systems.

Disadvantages of the Proposal: as it happens with other proposals based on DDS, implementation works have also to be carried out, as the standard provides only the framework to have that implementation done. In addition to that, the proposal itself does not explain with clarity the several services where the middleware architecture is expected to be used, as this piece of work seems more about showing how DDS can be adapted to the Smart Grid rather than showing an actual proposal that has already been designed and implemented.

32. Other Studies on the State of the Art for the Smart Grid

There are several other scientific works that, to an extent, describe the status of communications, networking solutions and middleware for the Smart Grid. Usually, the review of the available solutions in the scientific community results in the assessment of the proposals that have been developed in a survey. In the surveys regarding the State of the Art in this application domain, there are several features that have been taken into account, but unfortunately, they are flawed in several ways as far as middleware for the Smart Grid is concerned.

The survey that has been carried out by Wang *et al.* [82] is focused on the concept of how Energy Internet (EI) can be regarded as an emerging technology with several iterations. The authors put forward a way to describe the different entities that have been deemed as part of the idea of EI that has been conceived by them. They regard a component called FREEDM (Future Renewable Electric Energy Delivery and Management) as the core of their concept, as it would be capable of. Overall, although the information related to data treatment and transfer is solid, the concept of EI might be underplaying too much the importance of the already existing power grid and all its equipment. The authors also make some claims, such as "*Smart grid refers to one-way communication*" that are contested by the works of other authors.

Other survey that has been carried out by Wang *et al.* [83] also attempts to offer an Internet of Things architecture in a way that it can provide energy-efficient resources. As it happened with some middleware architecture proposals already described, the perspective that is provided in this piece of work makes use of three separated layers (sense, gateway and control) for data transfer purposes. The authors also provide a system model for energy-efficient IoT, a hierarchical framework with the aforementioned three layers and an activity schedule mechanism. As it happened in the previous proposal, though, the stress on the study done on the Internet of Things components, rather than in the Smart Grid itself, might be underrating the importance of having a power grid existing before the Internet era, and how there are many proposals that are counting on this for the deployment and development of the Smart Grid.

Wu *et al.* [84] have made a survey linking so-called green applications and big data. The authors comment on how big data analytics can help in the transition from nonrenewable to renewable resources, as well as how to improve Smart Grid management with them. The interest of the Smart Grid in big data comes as natural if it is taken into account how information is needed for service implementation, especially for some elements that belong to the middleware itself like the Advanced Metering Infrastructure, along with anything related to the power grid software infrastructure. Additionally, the importance of real-time big data is recognized too, but there is no information related to middleware developments for the Smart Grid in it, as the survey is focused on the application layer rather than the middleware one. Other works from Jinsong Wu *et al.* also mention how big data can be used to meet challenges related to sustainability. In the case of [85], big data has been ordered as a three-layer concept, with a services layer for end users, an infrastructure layer at the lowest level and a data organization, analytics and management between them to interface services and hardware.

Another example of the strong links between the Smart Grid and distributed systems in Information and Communication Technologies is in [78]. The relation between the Smart Grid and Reservoir Computing (RC) is studied as a way to describe how security measures can be applied to this environment against cyberattack actions, such as detection of False Data Injections (FDIs). The RC implementation shown in this manuscript is carried out via Delayed Feedback Networks (DFNs). Since reservoirs are implemented between the inputs and outputs of a system, there is a possibility of placing such reservoir as part of a middleware solution. Additionally, it is explained in [79] how Context Awareness is a concept of major importance for technologies like the IoT or middleware itself that have a significant resemblance with the Smart Grid. The authors of this piece of work depict how Context-Aware Communications and Networking (CACN). Finally, it is mentioned in [80] how the Smart Grid can be regarded as part of the effort in Information and Communication Technologies to be used as a way to contribute with the Sustainable Development Goals foreseen for year 2030.

Further research on the topic of Smart Grid and industry synergies is described in [72]. By reviewing the different articles devoted to this matter, it is mentioned in that piece of work the importance of four different aspects related to interoperability and interconnectivity at the data level in the Smart Grid: a) security and privacy for the information related to the Smart Grid and Renewable Energy Sources, b) communication and networking protocols, c) power flow and scheduling techniques, d) resource management and electricity pricing. This guest editorial, however, does not make an explicit mention to middleware as a component required to be included, nor it makes any significant contribution regarding how middleware should be present in the Smart grid or any power grid enhanced with ICT.

Li *et al.* [90] also make their own contributions describing the relation between Electric Vehicle Grid Integration (referred in the paper as EVGI) and Smart Cities. Their model rely on several key components that are deployed in a distributed manner: raw data and control information are used to make transactions between the Electric vehicles and a Wireless Access Network, that at the same time is used to transfer that information into a storage service based on cloud computing, which is storing data analytics tools as well as a forecasting system for Electric Vehicle power demand. Details on how to integrate vehicle-to-grid or Grid-to-vehicle technology are also offered by the authors of the proposal. However, middleware is not explicitly mentioned in this scientific proposal, nor there is any component that resembles or fully matches its functionalities.

It is mentioned as well in [91] how the Smart Grid can make use of Cognitive Radio (CR) as a way to take into consideration the existence of Quality of Service parameters. There are some other features that have been taken into account in this piece of work, such as a) CR-based smart home management, b) spectrum share, channel selection and Quality of Service management and c) reliability, trust and security. How smart homes are managed under a Smart Grid scenario is also a matter of discussion in this piece of work. Other than that, no mentions are made to middleware or any software layer used for hardware abstraction or interoperability.

Khan *et al.* [92] also mention how CR and MAC protocols are used in a Smart Grid-related scenario. In this work, a Cognitive Radio Network (CRN) is set by having several networks working cooperatively: a Wide Area Network, a CR base station and a Neighborhood Area Network composed by several Home Area Networks. There are several facilities that have been taken into account regarding the services expected to be offered, like building and home automation, demand response or real-time pricing. Unfortunately, there are no mentions done to middleware or how it can be used to integrate and interoperate among several vehicles. A wider, more detailed survey of the State of the art in Cognitive radio for Smart Grids has been carried out in [93]. In this case, how communications are established through a set of wireless networks resembling the previous work has been consider, but the study of the proposals that follow similar patterns is thorough and detailed. No explicit mentions are done to middleware or the intermediation software used for interoperability among the services and components used in a deployment.

The survey done by Martínez *et al.* [94] shows how middleware can be used in the Smart Grid to the advantage of this latter system. The solutions were included considering their main components, along with their description and functionalities. Main strengths and weaknesses were also mentioned. Even though this study is matching the idea of taking care of the State of the Art regarding middleware solutions for the Smart Grid, it is based on solutions that existed as of 2013, so even though many of the proposals are still valid at this point, some other proposals have become outdated at this point. Alas, middleware has become a more popular research topic since then, so the number of solutions that are available now is higher than previously. Nevertheless, since the middleware proposals that were studied are still part of the State of the Art, they have been included in this study and reviewed again with the new criteria introduced for this manuscript, which were absent in the survey aforementioned (software components, for example, are less significant or absent if the solution is not based on a middleware architecture).

In the study carried out by Yan *et al.* [95] the main topic of assessment is the applications and features that communications infrastructure makes possible in the Smart Grid. The authors provide their motivations for surveying this part of the application domain (customer experience, increased productivity, renewable resource generation, lower carbon fuel consumption, etc.). Among the reviewed topics, the main developments done in Power Line Communications (PLCs), Distributed Energy Resources (DERs), Advanced Metering Infrastructure or Monitoring and Controlling functionalities are taken into account. Among the requirements that are mentioned for an optimal performance of the system there are several of them that are closely related to middleware, such as Quality of Service, interoperability, scalability and security. The National Institute of Standards and Technology (NIST) framework for the Smart Grid is heavily taken into account by the authors, too [96].Unfortunately, this survey does not take into account why middleware is a desirable software entity to be added in the Smart grid, nor what its main features are (middleware is only mentioned as a way to transfer information via messages). Furthermore, the study portrays the energy flow as a one direction-only action, thus effectively not taking into account the energy input that prosumers could provide to the overall system.

In the survey done by Fang *et al.* [97], most of the main software and hardware features of the Smart Grid are covered. After describing what a Smart Grid can provide when compared to a regular power grid, the authors claim that the Smart Grid can be subdivided in three different subsystems: the *smart infrastructure system* (the facilities provided for energy, information and communication), the *smart management system* (it offers control and management services) and the *smart protection system* (delivers grid reliability analysis, privacy, security and failure protection, wired and wireless technologies, etc.). Each of the systems is further broken down to reflect the different studies that have been performed in their areas of interest (transmission system, management objectives). As it happened previously, the NIST conceptual model for the Smart Grid is also taken into account by this proposal. Among the future research works mentioned, interoperability among cryptographic systems, impact evaluation of increasing energy consumption and asset usage or decision making processes are mentioned. Despite the depth of the study and the extended classification for each of the solutions mentioned, middleware is not considered to play a prominent role in this study, so mentions to it are nonexistent.

Erol-Kantarci and Mouftah [98] introduce in their own survey on interactions and open issues how features related to energy efficiency are of major importance in order to use the Smart Grid to the advantage of end users. The authors of this survey divide the Smart Grid in three different subdomains: a) the *Smart Grid Home Area Network* (SG-HAN, a residential unit with smart appliances, storage, small-scale wind turbines and other power production and consumption control tools), b) the *Smart Grid Neighborhood Area Network* (SG-NAN, a group of houses likely to be receiving electricity from the same transformer) and c) *Smart Grid Wide Area Network* (SG-WAN, responsible for connecting SG-NANs with the utility operator). The authors claim that the stress on their survey relies on data centers and communication networks because they are quite very power-demanding. Therefore, their study is focused on assessing the proposals and solutions for the communication infrastructure in this application domain: wireless and wireline communications and optical networks are researched, along with energy efficiency in data centers. Although interoperability is mentioned as a characteristic to consider in this application domain, no mentions are done to middleware or how it is used to abstract hardware particularities or offer software services.

Cintuglu *et al.* [99] also present their own study in testbeds for the Smart Grid. The authors claim that test platforms, domains, research goals and communications infrastructure are born in mind in their survey. By domains, it is understood that they are a) *customer domain* (defines the end users as the ones present at homes, industries and commercial buildings), b) *market domain* (related to trading operations and services linked to retailing), c) *service provider domain* (deals with management operations for customers or buildings), d) *operation domain* (responsible for the reliable and safe operation of the power system), e) *bulk generation domain* (used for large scale generation units), f) *transmission domain* (operations related to TSOs), g) *distribution domain* (servers interconnectivity between the transmission and customer domains). All these domains are involved in testbeds that are of different nature: hardware-based, security-oriented, wide area control oriented, wireless communication oriented and interoperability and agent-based. As far as this survey is concerned, the existence of middleware services and how they are accessed is less important than the testbeds that are used for testing purposes, so middleware has been included just as another element that is part of the Smart Grid and tested (especially when real-time data is involved in testing activities), so there is very little information about the services it can provided or how it is distributed in the hardware components of a testbed.

Many other surveys on other very specific hardware and software technologies related to the Smart Grid or distributed, Cyber-Physical Systems have been carried out (security from a data-driven approach in [100], cellular communications for the Smart Grid in [101], standardization for cognitive radio technologies in [102], demand response programs in [103], smart home security in [104], geographic load balancing in [105], privacy preserving mechanisms in the Smart Grid [106], uncertainty analyses [107], etc.). However, they usually present similar issues: either they cover several topics of an application domain rather than a specific one or they do not study middleware as a major software component of the Smart Grid and are oblivious to its existence.

V. Open Issues

When all is said and done, the main features of the middleware solutions that have been described in this survey have been summarized in Table IV. It reflects how every proposal has been categorized according to the four main characteristics that were presented in Section II of the manuscript.

According to the results that have been obtained from the assessment done in each of the proposals, several open issues have been identified as of major importance in middleware solutions for the Smart Grid. Most of them are related to the limitations that a middleware proposal has regarding the quantity of services that can be offered by it and the devices that can be used to install the software components that are part of the solution. While the tasks that each of the middleware solutions has been conceived for are usually solved in a correct way, they have not conceived to be scalable or provide a range of services that will ease future or present scalability and interoperability.

The main advantages and disadvantages of the presented solutions have been summarized in Table V.

In the end, there are several challenges that have to be considered as common open issues that have been found in the analysis done on the middleware proposals that have been developed for the Smart Grid. Judging from their strengths

TABLE IV
PROPOSAL SUMMARIZATION

Proposal name	Service availability	Computational capabilities	Message coupling	Middleware distribution	References to the proposals
GridStat	Message-Oriented Middleware	TSO/DSO domain	Publish/ Subscribe	Mostly decentralized	[25]
Service-Oriented Middleware for Smart Grid	Middleware architecture	End user and aggregator domains	Client/Server	Mostly decentralized	[28]
Ubiquitous Sensor Network Middleware	Middleware architecture	End user, aggregator, TSO/DSO and power plant domains	Real time	Mostly decentralized	[29]
OHSNet	Middleware architecture	End user domain	Client/Server	Mostly decentralized	[30]
MDI	Middleware architecture	End user domain	Publish/ Subscribe	Mostly centralized	[31]
IEC 61850 and DPWS	Middleware architecture	TSO/DSO and power plant domains	Publish/ Subscribe	Mostly decentralized	[32], [33], [34], [35]
IAP-INMS	Middleware architecture	Aggregator, TSO/DSO and power plant domains	Publish/ Subscribe	Mostly decentralized	[36]
Self-Organizing Smart Grid Services	Abstraction middleware	End user and aggregator domains	Real time	Fully decentralized	[37], [38]
Secure Decentralized Data-Centric Information Infrastructure	Middleware architecture	End user, aggregator and TSO/DSO domains	Publish/ Subscribe, real time	Mostly decentralized	[38]
A cloud optimization perspective	Middleware architecture	End user, aggregator, TSO/DSO and power plant domains	Publish/ Subscribe, real time	Mostly decentralized	[39]
KT's Smart Grid Architecture and Open Platform	Middleware architecture	Aggregator, TSO/DSO and power plant domains	Publish/ Subscribe	Mostly decentralized	[43]
Smart microgrid monitoring with DDS	Message-Oriented Middleware	End user, aggregator and TSO/DSO domains	Publish/ Subscribe, real time	Mostly decentralized	[44]
ETSI M2M	Middleware architecture	End user, aggregator, TSO/DSO and power plant domains	Client/Server	Mostly decentralized, fully decentralized	[46]
Smart Middleware Device for Smart Grid Integration	Middleware architecture	Aggregator and TSO/DSO domains	Real time	Fully centralized	[48]
WAMPAC-based Smart Grid communications	Middleware architecture	End user and power plant domains	Publish/ Subscribe, real time	Mostly decentralized	[49]
C-DAX	Message-Oriented Middleware	TSO/DSO and power plant domains	Publish/ Subscribe, real time	Mostly decentralized	[51]
Building as a Service	Middleware architecture	Aggregator and TSO/DSO domains	Client/Server	Mostly decentralized	[52]
Middleware-based management for the Smart Grid	Abstraction middleware	End user domain	Client/Server	Mostly decentralized	[55]
OpenNode Smart Grid architecture	Abstraction middleware	End user, aggregator and TSO/DSO domains	Real time	Fully decentralized	[57], [58]
DIRECTOR	Intermediation middleware	End user, aggregator, TSO/DSO and power plant domains	Client/Server, real time	Fully decentralized	[59]
DDS interoperability for the Smart Grid	Message-Oriented Middleware	Aggregator and TSO/DSO domains	Publish/ Subscribe, real time	Mostly centralized	[62]
Distributed Middleware Architecture for Attack-Resilient Communications in Smart Grids	Intermediation middleware	TSO/DSO domain	Real time	Mostly centralized	[63]
Real-Time Middleware Platform based on ETSI M2M middleware	Middleware architecture	Aggregator and TSO/DSO domains	Client/Server, real time	Mostly decentralized	[64]
Apache Spark as distributed middleware	Abstraction middleware	End user, aggregator and TSO/DSO domains	Client/Server	Mostly centralized	[65]
High availability mesh network	Abstraction middleware	Aggregator and TSO/DSO domains	Client/Server	Mostly decentralized	[66]
Open System for Energy Services (OS4ES)	Intermediation middleware	Aggregator and TSO/DSO domains	Client/Server, real time	Fully centralized, mostly decentralized, fully decentralized	[67], [68]
Cloud-Based and RESTful Internet of Things Platform	Middleware architecture	End user, aggregator and TSO/DSO domains	Client/Server	Mostly decentralized	[69]
Software Defined Based Smart Grid Architecture	Middleware architecture	End user, aggregator and TSO/DSO domains	Publish/ Subscribe, real time	Mostly decentralized	[70]
Distributed Software Infrastructure for General Purpose Services	Middleware architecture	Aggregator, TSO/DSO and Power plant domains	Publish/ Subscribe, real time	Fully decentralized	[71]
Distributed Middleware Architecture for Attack-Resilient Communications	Message-Oriented Middleware	TSO/DSO domain	Real time	Fully decentralized	[72]
Tailoring DDS to Smart Grids for Improved Communication and Control	--	--	--	--	[73]

and weaknesses, the middleware for the Smart Grid presents these overall weaknesses:

1. *Lack of consistency in service availability:* There is not a clear list or criterion on what services should be included as part of a middleware solution. Furthermore, justification on how services should be provided is not provided either, as there are not clear boundaries regarding what components should be included in the middleware and the ones that do not need to be included. The lack of a clear procedure to fix the expected actions to be taken is also an issue when trying to reuse or port an already finished development, as it might force to create significant details of the implementation from scratch rather than using something that was already codified.
2. *No common solutions to access services:* An accurate procedure on how to access services from the higher (that is to say, an API used to access the middleware solution from the application layer) or lower layers (a data format used by all the devices transmitting information to the middleware and higher layers) is not provided.
3. *Ambiguity regarding middleware design:* When studying a proposal, sometimes it is not clear what is meant by "middleware", as it may end up including terms and concepts that are not part of it (applications, network layer). In other cases, middleware might end up located in a single device rather than distributed among several pieces

TABLE V
SUMMARIZATION OF ADVANTAGES AND DISADVANTAGES OF THE PROPOSALS

Proposal name	Advantages	Disadvantages	Resulting open issue
GridStat	Framework rich in details. Implementation activities have been carried out. It demands low computational capabilities.	Major services are not present. No implementation details of security, semantic capabilities or context awareness services.	Lack of available services
Service-Oriented Middleware for Smart Grid	Several services available. Performance tests have been carried out. Security has been taken into account.	Major services are not present. Data about distribution are missing. The limits defined for the solution are imprecise.	Lack of available services
Ubiquitous Sensor Network Middleware	Decentralization is enabled. Compatibility with a plethora of technologies.	The limits defined for the solution are imprecise. Very few data about the equipment where the proposal can be included. No performance tests have been added.	Lack of available services. Lack of performance information
OHSNet	Major set of services devoted to hardware interoperability.	The limits defined for the solution are imprecise. The services included do not provide much functionality for outer actors.	Lack of boundaries for middleware
MDI	It has very detailed information about hardware devices and their computational capabilities.	Very few data regarding implementation. Security or semantics have not been enabled.	Lack of performance information
IEC 61850 and DPWS	Information about semantic capabilities and implementation is provided. Security is part of the proposal.	Data about hardware abstraction of any tests that have been done to the proposal are scarce.	Lack of performance information
IAP-INMS	Data heterogeneity is explicitly dealt with. An ESB is used to encase services. Testing activities have been provided.	Little to no information about major services (security) or hardware abstraction.	Lack of available services
Self-Organizing Smart Grid Services	It has been conceived as highly distrusted.	No information regarding how to include the proposal in a deployment. Little to no information about testing activities. No major services included.	Lack of available services. Lack of performance information
Secure Decentralized Data-Centric Information Infrastructure	The solution is easy to port from one environment to other. Security and networking capabilities. An API is part of the solution.	Too much focus on network and transport layers. Major services like semantics are not included in the proposal.	Lack of boundaries for middleware

TABLE V
CONTINUED

Proposal name	Advantages	Disadvantages	Resulting open issue
A cloud optimization perspective	Distribution is well realized. Parallel tasks can be carried out. Security can be included.	Little information is present about the software elements of the proposal. No API is available.	Lack of available services
KT's Smart Grid Architecture and Open Platform	The platform that middleware is included in is an open development. A realistic deployment has been carried out.	End users are regarded as consumers (rather than prosumers) in the system. No information about security. No API is provided.	Lack of middleware as a differentiated concept. Lack of available services
Smart microgrid monitoring with DDS	DDS is a suitable standard for interoperability solutions. Computational capabilities match what is intended in the proposal.	Smart Grid services have to be developed from scratch.	Lack of available services
ETSI M2M	An API is given as part of the development works carried out. Can be ported to other systems.	Description of implemented services is somewhat confusing. Not much information about message transmission.	Lack of available services. Lack of information regarding middleware implementation
Smart Middleware Device for Smart Grid Integration	Testing activities with actual smart meters and technologies.	The proposal is conceived for a specific device. There is no information about how distribution is carried out. Major services are missing. No API is provided.	Lack of middleware as a differentiated concept. Lack of information regarding middleware implementation
WAMPAC-based Smart Grid communications	Security features are offered, along with information on how to build a testbed.	No information about other services unrelated to securitization. There is no API to be provided.	Lack of available services.
C-DAX	Components and use cases have been provided for testing activities. Security is offered as a service.	Other services aside from security are not described.	Lack of available services.
Building as a Service	An API and well-known software technologies (JSON, SOAP, JDBC, etc.) are offered as part of the proposal.	No data about major security services. The proposal is focused on a single scenario.	Lack of available services. Lack of information regarding middleware implementation
Middleware-based management for the Smart Grid	Great effort in improving Advanced Metering Infrastructure by means of middleware.	The middleware solution is strongly linked to a specific kind of hardware and software (CORBA, Ice).	Dependency on a specific technology.
OpenNode Smart Grid architecture	Very suitable for the power grid. Testing activities in realistic scenarios.	Middleware conceived for very specific purposes. No information about major middleware services.	Dependency on a specific technology. Lack of information regarding middleware implementation

(Continued)

of hardware, as it should be for hardware interoperability and abstraction in distributed, Cyber-Physical Systems. This disparity of definitions regarding what middleware is and how it should be dealt with creates issues when trying to accomplish interoperable systems that make use of a common idea of what should be regarded as middleware.

TABLE V
CONTINUED

Proposal name	Advantages	Disadvantages	Resulting open issue
DIRECTOR	Tests done with realistic hardware. Explicit features related to service distribution.	Major services are not present in the proposal. No API is offered. Scarce information about message coupling.	Lack of available services. Lack of information regarding middleware implementation
DDS interoperability for the Smart Grid	DDS is a suitable standard for interoperability solutions. A testbed has been made available.	The only main purpose of the proposal is high level and low level connectivity.	Lack of available services.
Distributed Middleware Architecture for Attack-Resilient Communications in Smart Grids	Thorough testing of security measures. Quality of Service and Experience are taken into account	Scarce information about middleware. No other remarkable services aside security	Lack of available services. Lack of information regarding middleware implementation
Real-Time Middleware Platform based on ETSI M2M middleware	The proposal has been tested in an actual scenario. Easy to access from the application layer	Scarce information about middleware and its services	Lack of available services. Lack of information regarding middleware implementation
Apache Spark as distributed middleware	Easy interoperability among systems	No major services available. Scarce information the distribution of the proposal in a deployed system	Lack of available services
High availability mesh network	Major stress in the importance of security. Tests have been carried out.	No other services available. Proposal focused on the network layer.	Lack of middleware as a differentiated concept. Lack of available services
Open System for Energy Services (OS4ES)	Functionalities and location of the proposal fall on what is expected from middleware	Proposal relying too much on the network layer. Not enough information about implemented services	Lack of middleware as a differentiated concept. Lack of available services
Cloud-Based and RESTful Internet of Things Platform	Functionalities and location of the proposal fall on what is expected from middleware. Significant collection of services	Some key components are missing. Deeper testing would have been welcomed.	Lack of available services. Lack of performance information.
Software Defined Based Smart Grid Architecture	Plenty of functionalities defined. APIs are provided for outer connectivity	The proposal covers areas outside of a middleware solution	Lack of middleware as a differentiated concept
Distributed Software Infrastructure for General Purpose Services	Significant collection of services available	Functionality overlapping with other system components	Lack of middleware as a differentiated concept
Distributed Middleware Architecture for Attack-Resilient Communications	Usage of widespread standard	Not many services are present in the proposal	Lack of available services.
Tailoring DDS to Smart Grids for Improved Communication and Control	Concepts and procedures are described accurately	Guidelines are presented rather than an actual implementation	Lack of middleware as a differentiated concept

4. *Ambiguity regarding middleware solution:* As a consequence of all the previously presented issues, there is no existing effort done in standardization of middleware for the Smart Grid, thus making harder the implementation works of a solution for interoperability and interconnectivity at the data level.

To a greater or a lower extent, all these issues are present in the middleware architectures that have been reviewed, and challenge the original idea of a middleware solution.

VI. CONCLUSION AND FUTURE WORKS

A thorough study has been carried out for the most significant middleware proposals that have been found. Firstly, an introduction of what middleware is, why it is useful to have it as part of the Smart Grid and what it should offer has been made. Afterwards, four different features that have been chosen and justified as the ones that are most important to consider in order to have a satisfactory solution (service availability, computational resources, message coupling, and distribution). Based on those characteristics, a taxonomy has been built as a way to better classify each of the middleware solutions. The taxonomy can also be used as a matrix that rearranges each of the intermediate levels of each characteristic to describe middleware proposals in a more accurate way. The study on the found solutions has included a description of its main elements, how they fulfil each of the four characteristics mentioned and the advantages and disadvantages that they present. They have also been characterized according to the matrix that has been defined for them. Lastly, the open issues found have been summarized as a way to have a clear view of the challenges that need to be addressed for middleware in the Smart Grid. From the study that has been carried out, it can be seen how there is a set of weaknesses that are widespread in the middleware solutions that have been found, which are: a) no clearly defined services to be offered by middleware, b) lack of a common and accepted way to access middleware functionalities, c) uncertainty about the concept of middleware and what kind of boundaries should encase it and d) absence of a consensual implementation, or at least a design, of what middleware for the Smart Grid should be.

Therefore, future works should be aimed at solving those four issues in a satisfactory way. Fortunately, there is a plethora of solutions that can be carried out in order to solve these challenges:

1. A collection of specific services should be defined for middleware implementations in the Smart Grid. A group of them should be considered mandatory: device registration, context awareness, or securitization should always be present. Also, having three different layers separated in terms of functionalities within middleware (one to interact with devices, other with the core functionalities and a third one for applications) seems to be common, at least for architectures, as a suitable solution.
2. A consensual Application Programming Interface could be used as a way to clearly specify how middleware services are accessed from the adjacent levels of the solution. While it would be primarily aimed at the layers surrounding middleware (devices, network, applications) it could also involve core components of it.
3. An accurate definition of middleware, what it is and contains, and what it does not, would come in handy to

set what components should be taken for granted, and which other ones are responsibility of other layers to provide. In this way, including network infrastructure or part of the applications can be avoided and development will be simplified.

4. A common design for middleware would be welcomed, as it is done in standards such as DDS. In this way, there could be several implementations following rules of design that make use of specific subsystems and components.

Thus, a suitable middleware solution for the Smart Grid would be one that a) has a collection of services that has been clearly defined by the community of researchers, scientists and developers, b) uses an API that defines how services will be accessed both from the applications and the hardware that has been added to a Smart Grid-like deployment, c) clearly defines boundaries between the network and the hardware located below it and the applications that make use of it and d) is compliant with a standard that describes which software subsystems are part of the middleware and the design of their components. Future works regarding middleware solutions for the Smart Grid must follow this direction.

References

[1] V. H. Díaz *et al.*, "Semantic as an interoperability enabler in Internet of Things," in *Internet of Things: Converging Technologies for Smart Environments and Integrated Ecosystems*, O. Vermesan and P. Friess, Eds. Aalborg, Denmark: River, 2013, pp. 315–342.

[2] X. Li, J.-F. Martínez, J. Rodríguez-Molina, and N. L. Martínez, "A survey on intermediation architectures for underwater robotics," *Sensors*, vol. 16, no. 2, p. 190, 2016.

[3] J. Rodríguez-Molina, J.-F. Martínez, P. Castillejo, and G. Rubio, "Development of middleware applied to microgrids by means of an open source enterprise service bus," *Energies*, vol. 10, no. 2, p. 172, 2017.

[4] J. Rodríguez-Molina, S. Bilbao, B. Martínez, M. Frasheri, and B. Cürüklü, "An optimized, data distribution service-based solution for reliable data exchange among autonomous underwater vehicles," *Sensors*, vol. 17, no. 8, p. 1802, 2017.

[5] F. L. Bauer, L. Bolliet, and H. J. Helms, "Software engineering: Report on a conference sponsored by the NATO science committee," NATO Sci. Committee, Garmisch, Germany, Rep. Jan. 1969. [Online]. Available: http://homepages.cs.ncl.ac.uk/brian.randell/NATO/nato1968.PDF AQ6

[6] W. Chongnan, W. Zongtao, and X. Hongwei, "Design of message-oriented middleware with publish/subscribe model on telemetry and command computer," in *Proc. 2nd Int. Conf. Syst. Informat. (ICSAI)*, Shanghai, China, 2014, pp. 454–458.

[7] M. Zemljic, I. Skuliber, and S. Desic, "Utilization of open-source high availability middleware in next generation telecom services," in *Proc. 17th Int. Conf. Softw. Telecommun. Comput. Netw. (SoftCOM)*, Hvar, Croatia, 2009, pp. 297–301.

[8] Z. Liu, J. Yu, X. Guo, T. Sun, and J. Zhang, "Survey of technologies of line commutated converter based high voltage direct current transmission in China," *CSEE J. Power Energy Syst.*, vol. 1, no. 2, pp. 1–8, Jun. 2015.

[9] A. Palade, C. Cabrera, G. White, M. A. Razzaque, and S. Clarke, "Middleware for Internet of Things: A quantitative evaluation in small scale," in *Proc. IEEE 18th Int. Symp. World Wireless Mobile Multimedia Netw. (WoWMoM)*, Macau, China, 2017, pp. 1–6.

[10] C. Perera, P. P. Jayaraman, A. Zaslavsky, P. Christen, and D. Georgakopoulos, "MOSDEN: An Internet of Things middleware for resource constrained mobile devices," in *Proc. 47th Hawaii Int. Conf. Syst. Sci.*, 2014, pp. 1053–1062.

[11] J. L. Poza-Lujan, J. L. Posadas-Yagüe, J. E. Simó-Ten, R. Simarro, and G. Benet, "Distributed sensor architecture for intelligent control that supports quality of control and quality of service," *Sensors*, vol. 15, no. 3, pp. 4700–4733, 2015.

[12] L. Aldred, W. M. P. van der Aalst, M. Dumas, and A. H. M. ter Hofstede, "Dimensions of coupling in middleware," *Concurrency Comput. Pract. Exp.*, vol. 21, no. 18, pp. 2233–2269, 2009.

[13] H. Kasai, "Embedded middleware and software development kit for area-based distributed mobile cache system," *IEEE Trans. Consum. Electron.*, vol. 59, no. 1, pp. 281–289, Feb. 2013.

[14] J. F. Inglés-Romero, A. Romero-Garcés, C. Vicente-Chicote, and J. Martínez, "A model-driven approach to enable adaptive QoS in DDS-based middleware," *IEEE Trans. Emerg. Topics Comput. Intell.*, vol. 1, no. 3, pp. 176–187, Jun. 2017.

[15] W. Chu, W. Li, T. Mo, and Z. Wu, "A context-source abstraction layer for context-aware middleware," in *Proc. 8th Int. Conf. Inf. Technol. New Gener.*, Las Vegas, NV, USA, 2011, pp. 1064–1065.

[16] V. Chevrin, S. Sockeel, and A. Derycke, "An intermediation middleware for supporting ubiquitous interaction in mobile commerce," in *Proc. ACS/IEEE Int. Conf. Pervasive Services*, Lyon, France, 2006, pp. 321–324.

[17] R. Bahsoon, W. Emmerich, and J. Macke, "Using real options to select stable middleware-induced software architectures," *IEE Proc. Softw.*, vol. 152, no. 4, pp. 167–186, Aug. 2005.

[18] R. Ramakrishnan and L. Gaur, "Smart electricity distribution in residential areas: Internet of Things (IoT) based advanced metering infrastructure and cloud analytics," in *Proc. Int. Conf. Internet Things Appl. (IOTA)*, Pune, India, 2016, pp. 46–51.

[19] J. Rodríguez-Molina, J.-F. Martínez, and P. Castillejo, "A study on applicability of distributed energy generation, storage and consumption within small scale facilities," *Energies*, vol. 9, no. 9, p. 745, 2016.

[20] K. S. Ko and D. K. Sung, "The effect of cellular network-based communication delays in an EV aggregator's domain on frequency regulation service," *IEEE Trans. Smart Grid*, to be published. AQ7

[21] R. Barella *et al.*, "A sensitivity based approach for efficient PMU deployment on smart grid," in *Proc. 4th Int. Conf. SMARTGREENS 1st Int. Conf. VEHITS Smart Cities Green Technol. Intell. Transp. Syst.*, Lisbon, Portugal, May 2015, pp. 199–215.

[22] T. Sattarpour, D. Nazarpour, S. Golshannavaz, and P. Siano, "A multi-objective hybrid GA and TOPSIS approach for sizing and siting of DG and RTU in smart distribution grids," *J. Ambient Intell. Humanized Comput.*, vol. 9, no. 1, pp. 105–122, 2018.

[23] X. Wu, X. Zhu, G.-Q. Wu, and W. Ding, "Data mining with big data," *IEEE Trans. Knowl. Data Eng.*, vol. 26, no. 1, pp. 97–107, Jan. 2014.

[24] L. Capra, "MaLM: Machine learning middleware to tackle ontology heterogeneity," in *Proc. 5th Annu. IEEE Int. Conf. Pervasive Comput. Commun. Workshops (PerCom)*, White Plains, NY, USA, 2007, pp. 449–454.

[25] P. Rathod, D. Sharma, and A. Golhani, "A topic-based publish-subscribe message broker for SCADA system using hierarchical subscription handling," in *Proc. Int. Conf. Adv. Comput. Commun. Control (ICAC3)*, Mumbai, India, 2017, pp. 1–10.

[26] J. C. Hastings and D. M. Laverty, "Modernizing wide-area grid communications for distributed energy resource applications using MQTT publish-subscribe protocol," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Chicago, IL, USA, 2017, pp. 1–5.

[27] N. Heard, P. Rubin-Delanchy, and D. J. Lawson, "Filtering automated polling traffic in computer network flow data," in *Proc. IEEE Joint Intell. Security Informat. Conf.*, The Hague, The Netherlands, 2014, pp. 268–271.

[28] H. Nishida and T. Nguyen, "Optimal client-server assignment for Internet distributed systems," *IEEE Trans. Parallel Distrib. Syst.*, vol. 24, no. 3, pp. 565–575, Mar. 2013.

[29] K.-D. Kim and P. R. Kumar, "Real-time middleware for networked control systems and application to an unstable system," *IEEE Trans. Control Syst. Technol.*, vol. 21, no. 5, pp. 1898–1906, Sep. 2013.

[30] P. B. M. Pedroso, "High availability and load balancing for postgresql databases: Designing and implementing," *Int. J. Database Manag. Syst.*, vol. 8, no. 6, p. 8, 2016.

[31] A. Kumar and B. Xie, Eds., *Handbook of Mobile Systems Applications and Services*, CRC Press 2016, sec. 8.5.6, p. 294. AQ8

[32] M. Wutzler, T. Springer, and A. Schill, "RoleDiSCo: A middleware architecture and implementation for coordinated on-demand composition of smart service systems in decentralized environments," in *Proc. IEEE 2nd Int. Workshops Found. Appl. Self Syst. (FASW)*, Tucson, AZ, USA, 2017, pp. 39–44.

[33] D. A. Croucher and H. A. Engelbrecht, "A peer-to-peer middleware plugin for an existing MMOG client-server architecture," in *Proc. IEEE Int. Workshop Haptic Audio Vis. Environ. Games (HAVE)*, Munich, Germany, 2012, pp. 140–141.

[34] H. Gjermundrod, D. E. Bakken, C. H. Hauser, and A. Bose, "GridStat: A flexible QoS-managed data dissemination framework for the power grid," *IEEE Trans. Power Del.*, vol. 24, no. 1, pp. 136–143, Jan. 2009.

[35] R. A. Johnston, C. H. Hauser, K. H. Gjermundrod, and D. E. Bakken, "Distributing time-synchronous phasor measurement data using the GridStat communication infrastructure," in *Proc. 39th Annu. Hawaii Int. Conf. Syst. Sci. (HICSS)*, 2006, p. 245b.

[36] E. S. Viddal, D. E. Bakken, H. Gjermundrød, and C. H. Hauser, "Wide-area actuator RPC over GridStat with timeliness, redundancy, and safety," in *Proc. Int. Conf. Complex Intell. Softw. Intensive Syst.*, Kraków, Poland, 2010, pp. 17–24.

[37] L. Zhou and J. J. P. C. Rodrigues, "Service-oriented middleware for smart grid: Principle, infrastructure, and application," *IEEE Commun. Mag.*, vol. 51, no. 1, pp. 84–89, Jan. 2013.

[38] A. Zaballos, A. Vallejo, and J. M. Selga, "Heterogeneous communication architecture for the smart grid," *IEEE Netw.*, vol. 25, no. 5, pp. 30–37, Sep./Oct. 2011.

[39] S. O. Park, J. S. Kim, and S. J. Kim, "An object-based middleware supporting efficient interoperability on a smart home network," *Multimedia Tools Appl.*, vol. 63, no. 1, pp. 227–246, 2013.

[40] Z. Li *et al.*, "A unified solution for advanced metering infrastructure integration with a distribution management system," in *Proc. 1st IEEE Int. Conf. Smart Grid Commun.*, Gaithersburg, MD, USA, 2010, pp. 566–571.

[41] S. Sucic, B. Bony, and L. Guise, "Standards-compliant event-driven SOA for semantic-enabled smart grid automation: Evaluating IEC 61850 and DPWS integration," in *Proc. IEEE Int. Conf. Ind. Technol.*, Athens, Greece, 2012, pp. 403–408.

[42] M. Adamiak, D. Baigent, and R. Mackiewicz. (2009). *IEC 61850 Communication Networks and Systems in Substations: An Overview for Users*. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.698.1497&rep=rep1&type=pdf

[43] OASIS Consortium. (2009). *Devices Profile for Web Services. Version 1.1*. [Online]. Available: http://docs.oasis-open.org/ws-dd/dpws/1.1/os/wsdd-dpws-1.1-spec-os.pdf

[44] D. Wang, Y. Zhu, P. Liu, J. Huang, and W. Zhao, "Research on distributed transmission of power telecontrol information based on ACSI/MMS," in *Proc. 3rd IEEE Conf. Ind. Electron. Appl.*, Singapore, 2008, pp. 670–674.

[45] A. P. García, J. Oliver, and D. Gosch, "An intelligent agent-based distributed architecture for Smart-Grid integrated network management," in *Proc. IEEE Local Comput. Netw. Conf.*, Denver, CO, USA, 2010, pp. 1013–1018.

[46] A. Awad and R. German, "Self-organizing smart grid services," in *Proc. 6th Int. Conf. Next Gener. Mobile Appl. Services Technol.*, Paris, France, 2012, pp. 205–210.

[47] Y.-J. Kim, M. Thottan, V. Kolesnikov, and W. Lee, "A secure decentralized data-centric information infrastructure for smart grid," *IEEE Commun. Mag.*, vol. 48, no. 11, pp. 58–65, Nov. 2010.

[48] X. Fang, D. Yang, and G. Xue, "Evolving smart grid information management cloudward: A cloud optimization perspective," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 111–119, Mar. 2013.

[49] W.-H. Liao, S.-C. Kuai, and Y.-R. Leau, "Auto-scaling strategy for Amazon Web services in cloud computing," in *Proc. IEEE Int. Conf. Smart City/SocialCom/SustainCom (SmartCity)*, Chengdu, China, 2015, pp. 1059–1064.

[50] S. Souidi, D. Boccio, S. Mierzwa, and J. Aguilar, "The feasibility of using microsoft azure infrastructure for a monitoring and evaluation system solution in sub-Saharan Africa," in *Proc. IEEE Glob. Humanitarian Technol. Conf. (GHTC)*, Seattle, WA, USA, 2015, pp. 226–232.

[51] P. Subhashini and S. Nalla, "Data retrieval mechanism using Amazon simple storage service and Windows Azure," in *Proc. 3rd Int. Conf. Comput. Sustain. Glob. Develop. (INDIACom)*, New Delhi, India, 2016, pp. 412–414.

[52] J. Lee, Y. Kim, J. Hahn, and H. Seo, "Customer energy management platform in the smart grid," in *Proc. 14th Asia–Pac. Netw. Oper. Manag. Symp. (APNOMS)*, Seoul, South Korea, 2012, pp. 1–4.

[53] K. Shi, Y. Bi, and L. Jiang, "Middleware-based implementation of smart micro-grid monitoring using data distribution service over IP networks," in *Proc. 49th Int. Universities Power Eng. Conf. (UPEC)*, Cluj-Napoca, Romania, 2014, pp. 1–5.

[54] Real Time Innovations. (2018). *RTI Connext DDS*. Accessed: Apr. 16, 2018. [Online]. Available: https://www.rti.com/products

[55] G. Lu, D. Seed, M. Starsinic, C. Wang, and P. Russell, "Enabling smart grid with ETSI M2M standards," in *Proc. IEEE Wireless Commun. Netw. Conf. Workshops (WCNCW)*, Paris, France, 2012, pp. 148–153.

[56] European Telecommunications Standards Institute. (2018). *ETSI The European Telecommunications Standards Institute: About ETSI*. Accessed: Apr. 16, 2018. [Online]. Available: http://www.etsi.org/about

[57] J. P. C. M. Oliveira, A. W. D. O. Rodrigues, R. C. Sá, P. Araújo, and A. L. C. de Araújo, "Smart middleware device for smart grid integration," in *Proc. IEEE 24th Int. Symp. Ind. Electron. (ISIE)*, Armação dos Búzios, Brazil, 2015, pp. 779–781.

[58] A. Ashok, A. Hahn, and M. Govindarasu "Cyber-physical security of wide-area monitoring, protection and control in a smart grid environment," *J. Adv. Res.*, vol. 5, no. 4, pp. 481–489, 2014.

[59] Y. Hu *et al.*, "NASPInet specification—An important step toward its implementation," in *Proc. 43rd Hawaii Int. Conf. Syst. Sci.*, Honolulu, HI, USA, 2010, pp. 1–9.

[60] C-DAX. Consortium. (2012). *Cyber-Secure Data and Control Cloud for Power Grids*. Accessed: Apr. 16, 2018. [Online]. Available: https://www.cordis.europa.eu/project/rcn/106390_en.html

[61] S. Martin, J. Hernandez, and C. Valmaseda, "A novel middleware for smart grid data exchange towards the energy efficiency in buildings," in *Proc. Int. Conf. Workshops Netw. Syst. (NetSys)*, Cottbus, Germany, 2015, pp. 1–8.

[62] OSGi Alliance Initiative. *OSGi Alliance*. Accessed: Apr. 16, 2018. [Online]. Available: https://www.osgi.org/about-us/

[63] J. Rodríguez-Molina, J.-F. Martínez, P. Castillejo, and L. López, "Combining wireless sensor networks and semantic middleware for an Internet of Things-based sportsman/woman monitoring application," *Sensors*, vol. 13, no. 2, pp. 1787–1835, 2013.

[64] D. Villa, C. Martin, F. J. Villanueva, F. Moya, and J. C. Lopez, "A dynamically reconfigurable architecture for smart grids," *IEEE Trans. Consum. Electron.*, vol. 57, no. 2, pp. 411–419, May 2011.

[65] Object Management Group. *CORBA*. Accessed: Apr. 16, 2018. [Online]. Available: http://www.corba.org/

[66] F. Leménager *et al.*, "Assessment and outlook of the OpenNode smart grid architecture," in *Proc. 22nd Int. Conf. Exhibit. Electricity Distrib. (CIRED)*, Stockholm, Sweden, 2013, pp. 1–4.

[67] OpenNode Consortium. (2012). *The OpenNode Project*. Accessed: Apr. 16, 2018. [Online]. Available: http://opennode.atosresearch.eu/

[68] J. Wilcox, D. Kaleshi, and M. Sooriyabandara, "DIRECTOR: A distributed communication transport manager for the Smart Grid," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Sydney, NSW, Australia, 2014, pp. 4227–4232.

[69] RS Components. *Raspberry Pi Model B*. Accessed: Apr. 16, 2018. [Online]. Available: http://docs-europe.electrocomponents.com/webdocs/127d/0900766b8127da4b.pdf

[70] R. de Diego, J.-F. Martínez, J. Rodríguez-Molina, and A. Cuerva, "A semantic middleware architecture focused on data and heterogeneity management within the smart grid," *Energies*, vol. 7, no. 9, pp. 5953–5994, 2014.

[71] T. A. Youssef, A. T. Elsayed, and O. A. Mohammed, "DDS based interoperability framework for smart grid testbed infrastructure," in *Proc. IEEE 15th Int. Conf. Environ. Elect. Eng. (EEEIC)*, Rome, Italy, 2015, pp. 219–224.

[72] Y. Wu, J. Wei, and B.-M. Hodge, "A distributed middleware architecture for attack-resilient communications in smart grids," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Paris, France, 2017, pp. 1–7. AQ9

[73] T. Predojev, A. Al-Hezmi, J. Alonso-Zarate, and M. Dohler, "A real-time middleware platform for the smart grid," in *Proc. IEEE Online Conf. Green Commun. (OnlineGreenComm)*, Tucson, AZ, USA, 2014, pp. 1–6.

[74] D. Šutic and E. Varga, "Apache spark as distributed middleware for power system analysis," in *Proc. 25th Telecommun. Forum (TELFOR)*, Belgrade, Serbia, 2017, pp. 1–4.

[75] T. A. Rizzetti *et al.*, "Security of communications on a high availability mesh network applied in smart grids," in *Proc. 50th Int. Univ. Power Eng. Conf. (UPEC)*, Stoke-on-Trent, U.K., 2015, pp. 1–6.

[76] J. Benze *et al.*, "Open system for energy services (OS4ES): An EU-funded research project to establish a non-discriminatory, multivendor-capability service delivery platform for smart grid services," in *Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Miami, FL, USA, 2015, pp. 593–598.

[77] OS4ES Consortium. *D1.2 OS4ES System Architecture, Component Requirements and Communication Infrastructure*. Accessed: Apr. 16, 2018. [Online]. Available: http://www.os4es.eu/Downloads/

[78] A. Meloni and L. Atzori, "A cloud-based and RESTful Internet of Things platform to foster smart grid technologies integration and re-usability," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC)*, Kuala Lumpur, Malaysia, 2016, pp. 387–392.

[79] Y. Jararweh, A. Darabseh, M. Al-Ayyoub, A. Bousselham, and E. Benkhelifa, "Software Defined based smart grid architecture," in *Proc. IEEE/ACS 12th Int. Conf. Comput. Syst. Appl. (AICCSA)*, Marrakech, Morocco, 2015, pp. 1–7.

[80] E. Patti *et al.*, "Distributed software infrastructure for general purpose services in smart grid," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 1156–1163, Mar. 2016.

[81] A. Alaerjan and D.-K. Kim, "Tailoring DDS to smart grids for improved communication and control," in *Proc. 5th Int. Conf. Smart Cities Green ICT Syst. (SMARTGREENS)*, Rome, Italy, 2016, pp. 1–6.

[82] K. Wang *et al.*, "A survey on energy Internet: Architecture, approach, and emerging technologies," *IEEE Syst. J.*, to be published.

[83] K. Wang, Y. Wang, Y. Sun, S. Guo, and J. Wu, "Green industrial Internet of Things architecture: An energy-efficient perspective," *IEEE Commun. Mag.*, vol. 54, no. 12, pp. 48–54, Dec. 2016.

[84] J. Wu, S. Guo, J. Li, and D. Zeng, "Big data meet green challenges: Big data toward green applications," in *IEEE Syst. J.*, vol. 10, no. 3, pp. 888–900, Sep. 2016.

[85] J. Wu, S. Guo, J. Li, and D. Zeng, "Big data meet green challenges: Greening big data," *IEEE Syst. J.*, vol. 10, no. 3, pp. 873–887, Sep. 2016.

[86] K. Hamedani, L. Liu, R. Atat, J. Wu, and Y. Yi, "Reservoir computing meets smart grids: Attack detection using delayed feedback networks," *IEEE Trans. Ind. Informat.*, vol. 14, no. 2, pp. 734–743, Feb. 2018.

[87] J. Wu *et al.*, "Context-aware networking and communications: Part 1 [guest editorial]," *IEEE Commun. Mag.*, vol. 52, no. 6, pp. 14–15, Jun. 2014.

[88] J. Wu, S. Guo, H. Huang, W. Liu, and Y. Xiang, "Information and communications technologies for sustainable development goals: State-of-the-art, needs and perspectives," *IEEE Commun. Surveys Tuts.*, to be published.

[89] M. H. Rehmani, M. Reisslein, A. Rachedi, M. Erol-Kantarci, and M. Radenkovic, "Guest editorial special section on smart grid and renewable energy resources: Information and communication technologies with industry perspective," *IEEE Trans. Ind. Informat.*, vol. 13, no. 6, pp. 3119–3123, Dec. 2017.

[90] B. Li, M. C. Kisacikoglu, C. Liu, N. Singh, and M. Erol-Kantarci, "Big data analytics for electric vehicle integration in green smart cities," *IEEE Commun. Mag.*, vol. 55, no. 11, pp. 19–25, Nov. 2017.

[91] M. H. Rehmani, A. Rachedi, M. Erol-Kantarci, M. Radenkovic, and M. Reisslein, "Cognitive radio based smart grid: The future of the traditional electrical grid," *Ad Hoc Netw.*, vol. 41, pp. 1–4, May 2016.

[92] A. A. Khan, M. H. Rehmani, and M. Reisslein, "Cognitive radio for smart grids: Survey of architectures, spectrum sensing mechanisms, and networking protocols," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 860–898, 1st Quart., 2016.

[93] A. A. Khan, M. H. Rehmani, and M. Reisslein, "Requirements, design challenges, and review of routing and MAC protocols for CR-based smart grid systems," *IEEE Commun. Mag.*, vol. 55, no. 5, pp. 206–215, May 2017.

[94] J.-F. Martínez, J. Rodríguez-Molina, P. Castillejo, and R. de Diego, "Middleware architectures for the smart grid: Survey and challenges in the foreseeable future," *Energies*, vol. 6, no. 7, pp. 3593–3621, 2013.

[95] Y. Yan, Y. Qian, H. Sharif, and D. Tipper, "A survey on smart grid communication infrastructures: Motivations, requirements and challenges," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 5–20, 1st Quart., 2013.

[96] National Institute of Standards and Technology. (2009). *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0*. Accessed: Apr. 16, 2018. [Online]. Available: https://www.nist.gov/sites/default/files/documents/public_affairs/releases/smartgrid_interoperability_final.pdf

[97] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid—The new and improved power grid: A survey," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 4, pp. 944–980, 4th Quart., 2012.

[98] M. Erol-Kantarci and H. T. Mouftah, "Energy-efficient information and communication infrastructures in the smart grid: A survey on interactions and open issues," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 179–197, 1st Quart., 2015.

[99] M. H. Cintuglu, O. A. Mohammed, K. Akkaya, and A. S. Uluagac, "A survey on smart grid cyber-physical system testbeds," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 446–464, 1st Quart., 2017.

[100] S. Tan, D. De, W.-Z. Song, J. Yang, and S. K. Das, "Survey of security advances in smart grid: A data driven approach," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 397–422, 1st Quart., 2017.

[101] C. Kalalas, L. Thrybom, and J. Alonso-Zarate, "Cellular communications for smart grid neighborhood area networks: A survey," *IEEE Access*, vol. 4, pp. 1469–1493, 2016.

[102] T. N. Le, W.-L. Chin, and H.-H. Chen, "Standardization and security for smart grid communications based on cognitive radio technologies—A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 423–445, 1st Quart., 2017.

[103] J. S. Vardakas, N. Zorba, and C. V. Verikoukis, "A survey on demand response programs in smart grids: Pricing methods and optimization algorithms," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 152–178, 1st Quart., 2015.

[104] N. Komninos, E. Philippou, and A. Pitsillides, "Survey in smart grid and smart home security: Issues, challenges and countermeasures," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 1933–1954, 4th Quart., 2014.

[105] A. Rahman, X. Liu, and F. Kong, "A survey on geographic load balancing based data center power management in the smart grid environment," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 214–233, 1st Quart., 2014.

[106] Y. Wu, Y. He, G. J. Mendis, and J. Wei, "A privacy-preserving middleware mechanism for smart grids," in *Proc. IEEE 2nd Int. Conf. Cloud Comput. Big Data Anal. (ICCCBDA)*, Chengdu, China, 2017, pp. 394–399.

[107] I. Akkaya, Y. Liu, and E. A. Lee, "Uncertainty analysis of middleware services for streaming smart grid applications," *IEEE Trans. Services Comput.*, vol. 9, no. 2, pp. 174–185, Mar./Apr. 2016.

Jesús Rodríguez-Molina, photograph and biography not available at the time of publication.

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